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July 1979

PROCEEDINGS: WORKSHOP ON THE NEED FOR LIGHTNING OBSERVATIONS FROM SPACE

HELD

FEBRUARY 13-15, 1979

AT

THE UNIVERSITY OF TENNESSEE SPACE INSTITUTE

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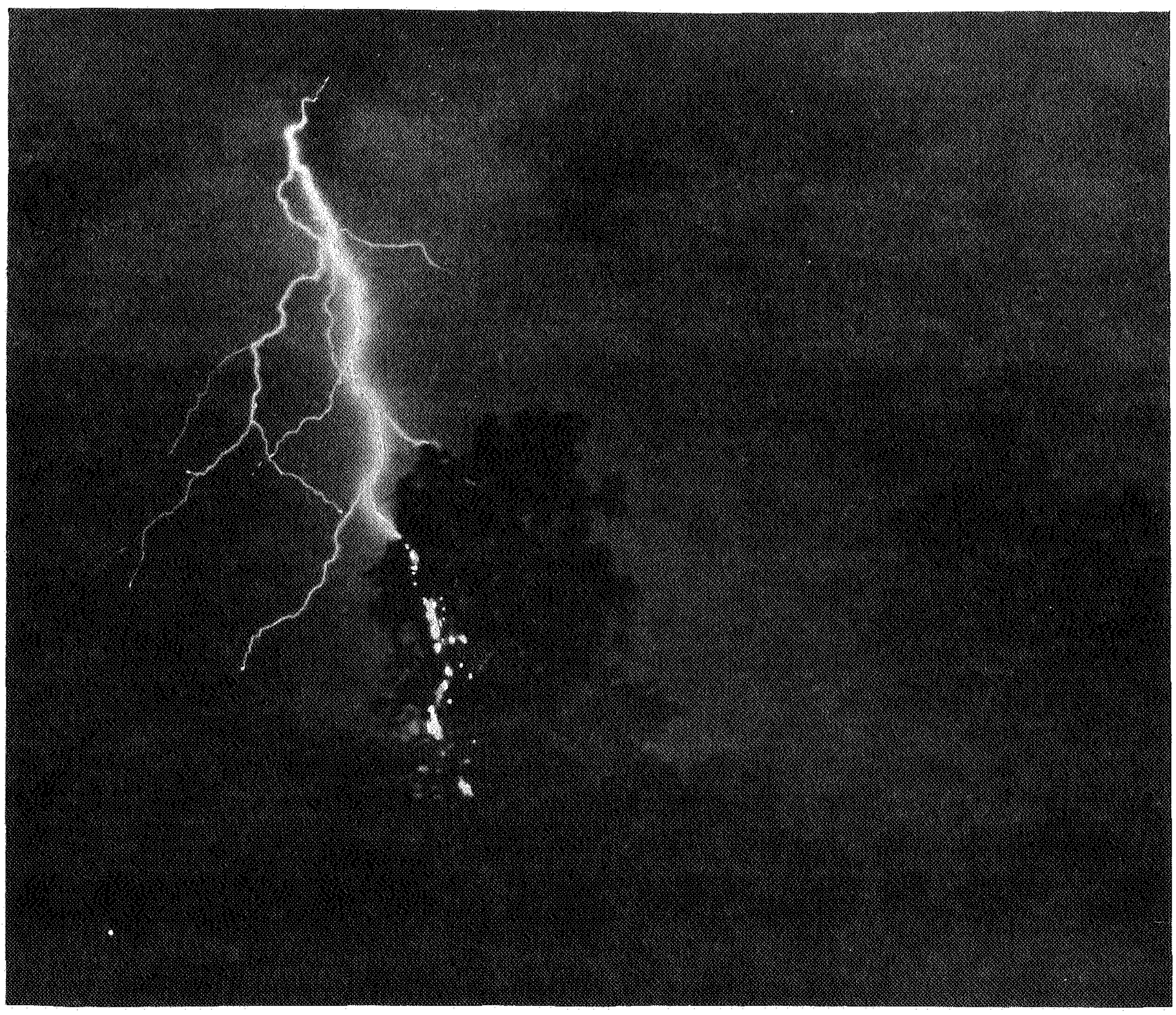

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16. ABSTRACT

This report presents the results of the Workshop on the Need for Lightning Observations from Space held February 13-15, 1979, at The University of Tennessee Space Institute, Tullahoma, Tennessee. The interest and active involvement by the engineering, operational, and scientific participants in the workshop demonstrated that lightning observations from space is a goal well worth pursuing. The unique contributions, measurement requirements, and supportive research investigations were defined for a number of important applications. Lightning has a significant role in atmospheric processes and needs to be systematically investigated. Satellite instrumentation specifically designed for indicating the characteristics of lightning will be of value in severe storms research, in engineering and operational problem areas, and in providing new information on atmospheric electricity and its role in meteorological processes.

This report supersedes NASA CP-2083, Workshop on the Need for Lightning Observations from Space—Preliminary Report, and should be used in place of it.

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ACKNOWLEDGMENTS

The accomplishments of the workshop are due to the dedicated efforts of many people in the scientific, engineering, and operations applications areas. In particular, the presenters of overview papers and the chairmen of the committees deserve much credit for the success of the workshop. The encouragement of Dr. James C. Dodge, Manager, Severe Storms and Local Weather Research Program, NASA Headquarters, was a major factor in the development of the workshop.

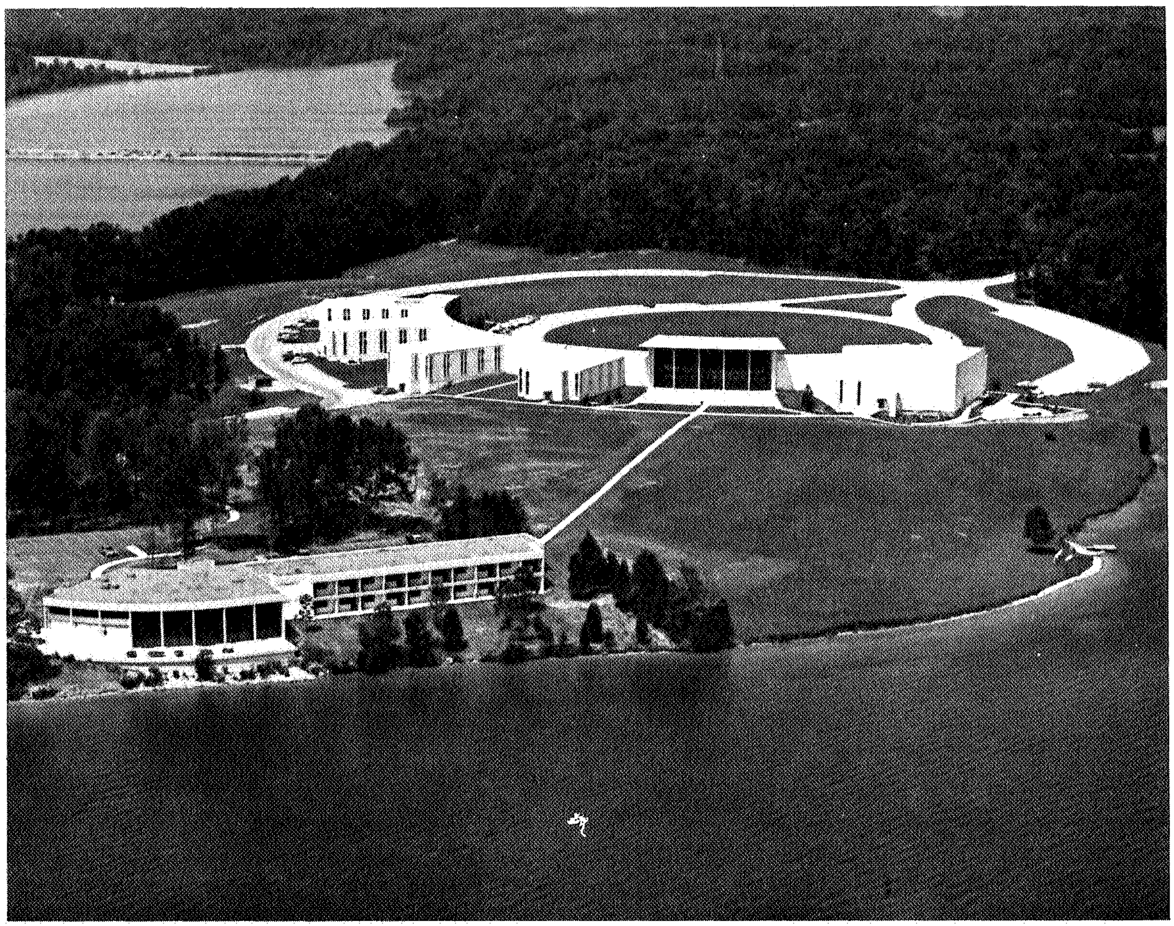
Thanks also go to The University of Tennessee Space Institute which, under the leadership of Dr. Walter Frost, expertly managed the logistics of the workshop with the dedicated help of Dr. Larry S. Christensen and Ms. Becky Durocher.

William W. Vaughan
Workshop Chairman

WORKSHOP ON THE NEED FOR LIGHTNING OBSERVATIONS FROM SPACE

TABLE OF CONTENTS

SECTION I -- EXECUTIVE SUMMARY



THE UNIVERSITY OF TENNESSEE SPACE INSTITUTE

EXECUTIVE SUMMARY

The interest and active involvement by the engineering, operational, and scientific participants in the workshop demonstrated that lightning observations from space is a goal well worth pursuing. The unique contributions, measurement requirements, and supportive research investigations were defined for a number of important applications. Lightning has a significant role in atmospheric processes and needs to be systematically investigated. Satellite instrumentation specifically designed for indicating the characteristics of lightning will be of value in severe storms research, in engineering and operational problem areas, and in providing new information on atmospheric electricity and its role in meteorological processes.

INTRODUCTORY REMARKS

A Workshop on the Need for Lightning Observations from Space was held February 13-15, 1979, at The University of Tennessee Space Institute, Tullahoma, Tennessee. This workshop was the result of an earlier exploratory meeting held April 10-11, 1978, and reported in NASA CP-2056, "Exploratory Meeting on Atmospheric Electricity and Severe Storms," July 1978. The application of space technology to the solution of the principal scientific and applications problems in atmospheric electricity was addressed. The participants at the workshop stressed that space technology can be applied fruitfully to the study of lightning phenomena. Direct lightning observations from satellites will be helpful in developing a better understanding of lightning and its relationship to severe storms plus a variety of important engineering and operational applications.

Several research areas are very well suited for experimentation using satellites; namely, the atmospheric electric global circuit and generator concept; the interrelationships between electricity, dynamics and microphysics in atmospheric processes; and the electrical activity associated with thunderstorm development, growth, and intensity. For severe storms application, priority should be given to the development of a lightning survey instrument system to provide a synoptic observational capability from geosynchronous orbit. However, efforts should also be made to exploit the space technology opportunities associated with currently approved flight instruments and orbiting platforms.

Techniques for measuring 1ightning activitity from space involve detecting electromagnetic radiation that is produced by the lightning discharge. This radiation ranges from radio frequencies to light in the visible on into the ultraviolet portion of the spectrum. A variety of options are therefore available in the design of the apparatus. The use of detectors in the short wave region appears attractive in view of the much smaller apparatus that is required to give sufficient directional information to identify electrically active clouds. The use of longer wavelengths will probably afford greater sensitivity in the detection of lightning during daylight hours. A certain amount of sensor development research remains to be conducted relative to atmospheric electricity measurement requirements in order to establish the optimum components and technology for application to space-based instruments.

Since there is ample evidence of potentially significant contributions to be derived from space-based lightning observations, the NASA Severe Storms and Local Weather Research Program intends to sponsor selected research and experimental investigations and a space flight sensor study that will define the needed satellite system. All user requirements cannot be satisfied simultaneously; however, it appears feasible at this time that a lightning detection system can be developed which will satisfy many user requirements.

MATRIX OF NEEDS, REQUIREMENTS, AND RECOMMENDATIONS

A brief review of the scientific information needs and requirements of various government agencies and other organizations (i.e., electric and telephone utilities, railroads, petroleum, etc.) concerned with the effects of lightning and a brief look at present sensor capabilities are presented in this summary. The significant points and aspects delineated by each committee are incorporated into each matrix.

The principal points of the workshop are summarized in the following tables under these topics:

A. BASIC SCIENTIFIC NEEDS

B. OPERATIONAL AND ENGINEERING APPLICATION REQUIREMENTS

C. COMMENTS ON MEASUREMENT TECHNIQUES AND RECOMMENDATIONS

D. INVESTIGATION RECOMMENDATIONS

E. NEEDS TO MEET VARIOUS USER REQUIREMENTS

A. BASIC SCIENTIFIC NEEDS

Subject	Scientific Questions
Meteorology of Electrification and Lightning Production	How are electrification and meteorology connected? What is the connection between storm dynamics and precipitation, and electrification? How is storm height correlated with electrification? Can small clouds produce lightning? Can warm clouds produce lightning? Are there severe storm-lightning correlations?
Thunderstorm Climatology	Is there a global thunderstorm activity diurnal cycle? Is thunderstorm activity over land greatly different from that over the oceans? Are there seasonal or yearly variations in thunderstorm activity? Does solar activity influence global thunderstorm activity?
Cloud Electrification	How are clouds electrified? What are the conditions for lightning production? How much lightning is produced?
Nitrogen Fixation	How much does lightning contribute to global nitrogen fixation? What is the correlation between lightning and other trace species?
Global Circuits	Is there a DC component of current in thunderstorms?

B. OPERATIONAL AND ENGINEERING APPLICATION REQUIREMENTS

SUMMARY TABLE

Real Time

USER	GEOGRAPHIC AREA	SPATIAL RESOLUTION GOAL	SPATIAL RESOLUTION MAX	SPATIAL RESOLUTION GOAL	SPATIAL RESOLUTION MAX	EVENT/RATE OR INTENSITY	DIRECTION	SPEED	CLOUD/GROUND OR INNER CLOUD DISCRIMINATION	FALSE ALARM	FAIL TO DETECT
Utilities	CONUS	±2 mi	±5 mi	10 min	20 min	Yes	Yes				
FAA	CONUS	±3 mi	5 mi	20 sec	1 min in terminal area--- 5 min on route	Yes	5-10°				
Telecommunications	None										
Forecasting	CONUS	±2 mi	±15 mi	15 min	60 min	Yes	5-10°	±2.5 m/sec	Yes	30%	10%
Forest Service Fire Detection	CONUS	250 m	1 km	5 min	20 nin	Yes	Yes	Yes	Yes, with continuing current monitor	10%	10%
Forest Service Storm Tracking	Western USA	±2 mi	±5 mi	15 min	45 min	Desirable	--	--	--	30%	10%
US Air Force (Best Estimate)	Worldwide	±3 mi	5 mi	5 min	10 min	Yes	15-10'	±2.5 m/sec	No	30%	10%

Research Information

USER	GEOGRAPHIC AREA	DIURNAL INFORMATION	EVENT RATE	CURRENT WAVEFORMS RISE & FALL TIME & PEAK MAGNITUDE	STORM SIZE	STROKES/FLASH	SEVERE STORM MONITORING	RATIO OF INNER CLOUD TO GROUND DISCHARGES	RELATIONSHIP BETWEEN LIGHTNING & RAIN
Utilities	CONUS	Yes	Yes	Yes	Yes	Yes	No	Yes	No
Telecommunication	CONUS	No	Yes	Yes	Yes	Yes	No	Yes	No
Forecasting	CONUS	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
US Air Force	Worldwide	Yes	Yes	Yes	Yes	Yes	No	Yes	No
FAA	CONUS	No	No	Yes	No	Yes	No	Yes	No
Forestry Service	CONUS	No	No	No	No	No	No	No	Yes

SYNOPSIS

Subject	Requirements
Real-Time Lightning Measurement	Location of activity is required to 250 meters (by Forest Service), up to 25 kilometers (by forecasting personnel), with typical location requirements by users being approximately 3 to 8 kilometers. Lightning event rates and intensity are required. Time resolution required is typically from 5 to 15 minutes, with FAA requiring 1 minute or less. Cloud-to-ground and intracloud discrimination is required by some users. Rise times and stroke currents are needed.
Long-Term, Global Lightning Measurement	Update of isokeraunic maps is necessary to provide fine detail and to locate areas of high levels of activity. Correlations of lightning with intensity of precipitation are needed.
Geophysical Distribution of Lightning Activity	Measurement of ground flash frequency as a function of geographic location is required. Total lightning activity needs to be measured as a function of geographic location. Associated storm size and duration are needed.
Measurement of Lightning Characteristics	The following are needed: • Current rise characteristics • Peak current • Duration of stroke • Duration of flash • Number of strokes per flash • Amplitude and duration of continuing current

C. COMMENTS ON MEASUREMENT TECHNIQUES AND RECOMMENDATIONS

Subject	Comments
Optical Techniques	Can we distinguish between intracloud and cloud-to-ground lightning? Does any relation exist between radiation and current? What are the characteristics of cloud-to-ground and intracloud flashes? What are the characteristics of flashes observed from above clouds? What is the signal-to-noise ratio of background characteristics? How much energy is radiated by lightning as a function of wavelength and how much can be expected to reach a satellite?
Optical Measurement of Lightning Flashes	Measurements of intercloud flash and cloud-to-ground flash and their discrimination (possibly by combining optical and RF measurements) are required. What are the spectral characteristics of the cloud-to-ground and intracloud lightning flash? To what degree can lightning be detected against daylight background conditions?
Optical Instrumentation for a Lightning Measuring Satellite	Resolution of 4 kilometers with a field of view of hundreds of a kilometer is reasonable. DMSP satellite sensors currently making measurements. Time resolution versus sensitivity trade-off must be made. High-speed data processing is needed on board.
Electromagnetic Techniques	Will one be able to discriminate between the lightning signal and ionospheric background noise? Can we achieve acceptable spatial and temporal resolution?

C. Comments on Measurement Techniques and Recommendations (Continued)

	What are the background noise levels at geosynchronous altitudes? What limitations might water vapor and the ionosphere have on propagation? What kind of information might one obtain at the different frequencies?
DC Component of Currents in Thunderstorms	Measurement from low-altitude satellites (100 to 200 km) would be required. Discrimination of signal from ionospheric background noise might be difficult.
VLF Emissions (up to 150 kHz)	The ionosphere is a good conductor in this frequency range. This frequency is probably not suitable for studying thunderstorms.
150 kHz to 5 MHz Emissions	Degree of application not determined.
5 to 30 MHz Emissions	Global sferics mapping by Japanese Ionospheric Sounding Satellite (ISS-2) is currently in progress.
30 MHz to 1 GHz Emissions	Large antennas are required. Background noise levels at geosynchronous altitudes are unknown. (Time resolution versus signal-to-noise trade-off study will be needed.) Flash rate counting is possible. Stroke characteristics can possibly be inferred. Little attenuation by water is a requirement.
1 GHz Infrared Emissions	There is very little knowledge about emissions in this region. Background noise levels are unknown. Water vapor and the ionosphere might limit propagation at these frequencies. Spatial resolution would be large at these frequencies.

C. Comments on Measurement Techniques and Recommendations (Concluded)

Satellite Sensor System Design Considerations	What spatial resolution can be achieved? What is the maximum sensitivity that can be obtained consistent with the desired spatial resolution? What is the data management need (real time versus delayed transmission, etc.)? What is the most appropriate time resolution? What is a reasonable conceptual instrument system design?
Ground Truth	Correlations between ground observation of lightning and the optical RF signatures observed from above are required. What percentage of lightning which occurs in the field of view is detected?

D. INVESTIGATION RECOMMENDATIONS

- Relate aircraft measurements to optical signatures and to ground truth data on peak currents, wave shape (VLF), and location within the clouds.
- Investigate noise problems of receivers in synchronous orbits.
- Investigate resolution versus economy problems (size, frequency, multiple use, scanning techniques).
- Compromise user requirements within trade-off dilemma and design first space equipment.
- Analyze distribution of thunderstorm currents at 100 to 200 km altitude.
- Prepare experiment to verify theory and thunderstorm detection concept.
- Interact with solar-weather, middle atmosphere, and upper atmosphere research programs.

D. Investigation Recommendations (Concluded)

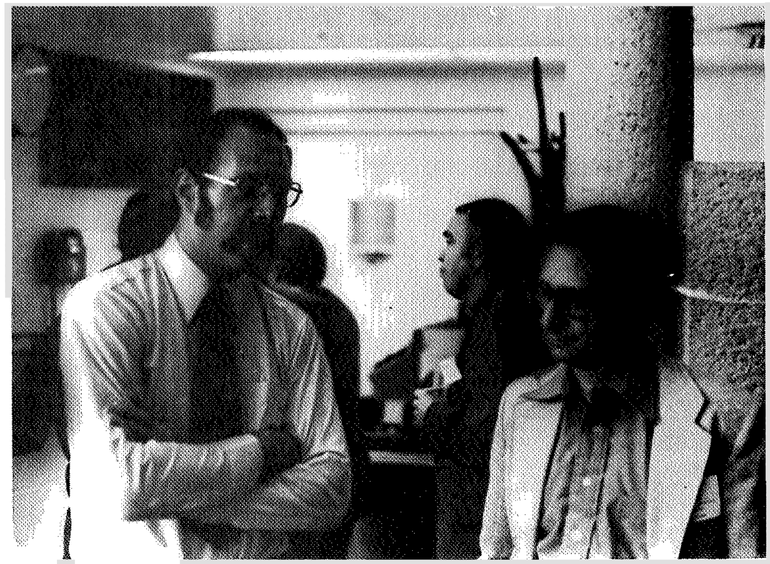
- Determine the spectral characteristics of the intracloud and cloud-to-ground lightning flashes.
- Determine the degree to which lightning can be detected above clouds against daylight background conditions.
- Design a reasonable conceptual instrument for a lightning detection system using experience from DMSP and other satellite sensor operations.
- Determine how much energy in the optical region propagates through a cloud.
- Examine the spectral characteristics of lightning as observed from space.
- Investigate the degree to which intracloud and cloud-to-ground lightning can be distinguished.
- Determine what percentage of lightning which occurs in the field of view is detected.
- Determine what spatial and temporal resolution can be achieved.
- Establish the maximum sensitivity that can be obtained consistent with the desired spatial resolution.
- Examine the possibility of relation between radiation and current.
- Determine the signal-to-noise ratio of background characteristics.
- Investigate lightning signatures from 100 MHz to 100 GHz.
- Establish more "numbers" (e.g., How much energy is radiated by lightning as a function of wavelength and how much can be expected to reach a satellite?).
- Establish a graduated program of research to improve our capabilities in lightning measurements from satellites. This would involve aircraft measurements over thunderstorms, probably utilizing U-2 aircraft; measurements from the Space Shuttle; and increasing planned use of lightning detectors on satellites. In addition, flights of opportunity should be sought.
- Include ground-based measurements of lightning to relate the severe storm activity to the radar, aircraft, and satellite data when conducting mesoscale meteorological experiments such as SESAME or the activities of the Convective Storms Division of NCAR.
- Conduct further research on the information content of the entire spectrum of emissions for optical through high radio frequencies from thunderstorms when viewed from above the clouds.

E. NEEDS TO MEET VARIOUS USER REQUIREMENTS

- A high-resolution (space-time) geostationary and/or orbital lightning detection system for global and regional measurements.
- Reasonable conceptual instrument designs.
- On-board high-speed data processing.
- Detector arrays with real-time resolution.
- Large aperture, large field-of-view, lightweight optics.
- 100 to 1000 MHz system.
- Large interferometer (phase or time-of-arrival).
- Adaptive scanner (guided by IR cloud detector).
- Smart filters (to deduce flash rate, peak current, and rise times).
- Multiple beam technology.
- Phase array.
- Multiple use (real time and research).
- Resolution (1 to 4 km for 200 x 200 km coverage).
- Sensitivity of at least 10^9 watts for global measurements, with approximately 10^7 watts desired for regional storm movements. (Time resolution will be obtained at the expense of sensitivity.)
- Spectral isolation of the signal.
- Accurate platform pointing.

SECTION I

INTRODUCTION



INTRODUCTION

This document provides a summary of the Workshop on the Need for Lightning Observations from Space which was held February 13-15, 1979, at the University of Tennessee Space Institute, Tullahoma, Tennessee. The motivation for this workshop resulted from the goals and objectives of the Severe Storms and Local Weather Research Program at NASA's Office of Space and Terrestrial Applications and a recent exploratory meeting* on atmospheric electricity and storms which was held April 10-11, 1978, at NASA George C. Marshall Space Flight Center, Alabama. The applicable goals and objectives of NASA's Severe Storms and Local Weather Research Program have been used to set the primary frame of reference for this report. It is within this framework, and the interest of NASA to provide the broadest practical application of space technology, that the future courses of action relative to the development of space technology for observation and measurement of atmospheric electrical phenomena will be developed for support and sponsorship by NASA's Office of Space and Terrestrial Applications.

The goal of the Severe Storms and Local Weather Research Program is: "to aid the responsible storm forecasting agencies in improving the accuracy and timeliness of severe storms forecasts and warnings through research and development that combines aeronautical and space-related techniques and observations with other key indicators of severe storm development." This will be accomplished through the sponsorship of severe storms research and development to improve the basic understanding, instrument development, data interpretation, technique development, and forecast model development. Atmospheric electricity is an integral part of severe storms and the meteorological phenomena associated with their development, growth and intensity. Optical and other electromagnetic signals are one of nature's best indicators of severe storms. Thus, the study of atmospheric electricity provides the opportunity to help accomplish the program objectives associated with the conduct of applied research for understanding storm development, development of new space technology storm severity indicators, demonstration of utility of analysis and interpretation techniques, and development of severe storms models to enable improvement of storm forecasting and lightning hazard warning capabilities.

The objectives of the workshop were to (1) identify the unique contributions which space observations can make to the identification and measurement of lightning and lightning-related characteristics, (2) establish measurement requirements for a space platform sensor system, and (3) determine the minimum supportive investigations required to relate space observables to users' needs. These objectives were achieved by providing a forum for information exchange on the research, engineering and operational benefits from a space platform sensor

*See NASA CP-2056.

system designed to measure lightning and lightning-related characteristics. The forum identified the current state of knowledge and users' needs and also examined the relationships of measurable lightning characteristics to severe storms.

The workshop was organized about committees whose responsibility it was to drive out the information listed in the objectives. The committees were organized into two principal groups: one advancing the viewpoints of the potential users of the information to be obtained by lightning observations from space and one supplying knowledge concerning sensing techniques. The user committees and their chairmen were:

Atmospheric Electricity and Meteorology -- Frank Eden
National Science Foundation

Engineering Applications -- Edwin Whitehead*
University of Colorado

Operational Applications -- Rodney Bent
Atlantic Science Corporation

Sensing techniques committees and their chairmen were:

Optical Techniques -- Richard Orville
State University of New York at Albany

Electromagnetic Techniques -- Lothar Ruhnke
Naval Research Laboratory

The user committees operated under the following guidelines:

1. From your interactions with the other committees, identify in order of decreasing importance the most pressing problems within the context of your committee's title,

2. State the physical observables required for solution of each problem,

3. State what potential values you see from observing these from space,

4. State whether prefeasibility experiments or analyses are required and define what these are,

5. Suggest the techniques for measurements from space and contrast with other methods,

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*Substituting for John Robb, Lightning and Transients Research Institute

6. Itemize for each observable the measurement parameters, for example: location and time of occurrence, space and time resolution, band width, frequency of observation (minimum sampling time), spatial coverage,

7. Give the data requirements, output format and characteristics required, and

8. State whether ground truth programs are required and list their requirements.

The sensing techniques committees operated under the following guidelines:

1. From your interactions with the other committees, identify in order of importance the most pressing problems within the context of your committee's title,

2. Identify the technology needs to meet the requirements presented by the users,

3. Report on the current state-of-the-art technology in space platform sensors available for each problem posed,

4. State what alternative solutions are possible for the problems, and

5. Insure that the user committees provide an adequate definition of the requirements to be met by the sensor systems.

The workshop was attended by leading investigators in the area of atmospheric electricity and severe storms, individuals familiar with the needs and requirements of potential users, and individuals knowledgeable in lightning emissions from upper atmospheric propagation and sensors. The interaction between the different committees and the variety of scientific interests involved proved very beneficial, and each of the committees made a significant contribution to the overall success of the workshop.

Table 1 is an outline of the agenda for the Workshop on the Need for Lightning Observations from Space.

In parallel with this workshop a Workshop on the Role of the Electrodynamics of the Middle Atmosphere on Solar-Terrestrial Coupling was held January 17-19, 1979, under the sponsorship of NASA's Office of Space Science (NASA CP-2090). Investigations of the electric fields in the middle atmosphere are useful since they contribute to the understanding of lower atmosphere electrical phenomena. At the Lightning Observations workshop the topic of middle atmospheric electric field measurements was, therefore, referred to the expertise of the Middle Atmosphere Electrodynamics workshop.

TABLE 1 -- WORKSHOP AGENDA

TUESDAY, FEBRUARY 13, 1979

7:45-8:30 REGISTRATION

8:30-9:00 WELCOME

William W. Vaughan
Chief, Atmospheric Sciences Division
NASA George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

WORKSHOP LOGISTICS

Walter Frost
Director, Atmospheric Science Division
University of Tennessee Space Institute
Tullahoma, Tennessee 37388

9:00-12:00 OVERVIEW PAPERS SESSION

Chairman — W. David Rust
National Severe Storms Lab/NOAA
1313 Halley Circle
Norman, Oklahoma 73069

Lightning Processes and Associated Emissions — Marx Brook

The History of Lightning Observation from Space — Bobby Turman

The State of Technology in Optical Sensors — Bruce Edgar

The State of Technology in Electromagnetc (RF) Sensors — Thomas Shumpert

The Requirements and Interests of the Forestry Industry — Dale Vance

The Commercial Requirements and Interests of the Power Industry — Robert Frech

The Comnercial Requirements and Interests of the Communications Industry — Oley Wanaselja

The Requirements and Interests of the Aviation Community — Philip Corn

1:00-2:30 INDIVIDUAL COMMITTEE MEETINGS

2:30-5:50 JOINT COMMITTEE MEETINGS

6:30 SOCIAL AT AEDC OFFICERS CLUB

7:15 BANQUET AT AEDC OFFICERS CLUB

Speaker – John Butler
Engineer
NASA George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

WEDNESDAY, FEBRUARY 14, 1979

8:30-8:45 HOW GOES IT SESSION

8:45-10:00 OVERVIEW PAPERS SESSION

Chairman – Arthur A. Few, Jr.
Department of Space Physics
Rice University
P.O. Box 1892
Houston, Texas 77001

Global Circuit and Generator Mechanisms – Heinz Kasemir

Current Sponsored Atmospheric Electricity Research and Future Program Goals at the National Science Foundation – Frank Eden

Current Sponsored Atmospheric Electricity Research and Future Program Goals at the Office for Naval Research – Lothar Ruhnke (for James Hughes)

Potential Use of Lightning as an Indicator of Storm Severity – James Dodge

10:30-12:00 JOINT COMMITTEE MEETINGS

1:00-3:00 JOINT COMMITTEE MEETINGS

3:30-5:00 INDIVIDUAL COMMITTEE MEETINGS

6:00 DINNER AT UTSI

Speakers – C. H. Weaver
Dean and Vice President for Continuing Education
University of Tennessee Space Institute
Tullahoma, Tennessee 37388

Arthur A. Few, Jr.
Department of Space Physics
Rice University
Houston, Texas 77001

Richard Orville
Department of Atmospheric Sciences
State University of New York at Albany
Albany, New York 12222

THURSDAY, FEBRUARY 15, 1979

8:30-9:15 INDIVIDUAL COMMITTEE MEETINGS

9:15-12:15 COMMITTEE REPORTS SESSION

Chairman — William W. Vaughan
Chief, Atmospheric Sciences Division
NASA George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Summary of Sensing Techniques Committee Reports —

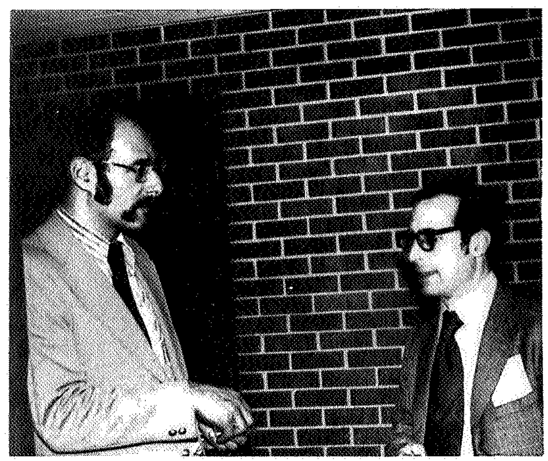
Electromagnetic Techniques
Optical Techniques

Summary of User Committee Reports —

Operational Applications
Engineering Applications
Atmospheric Electricity and Meteorology

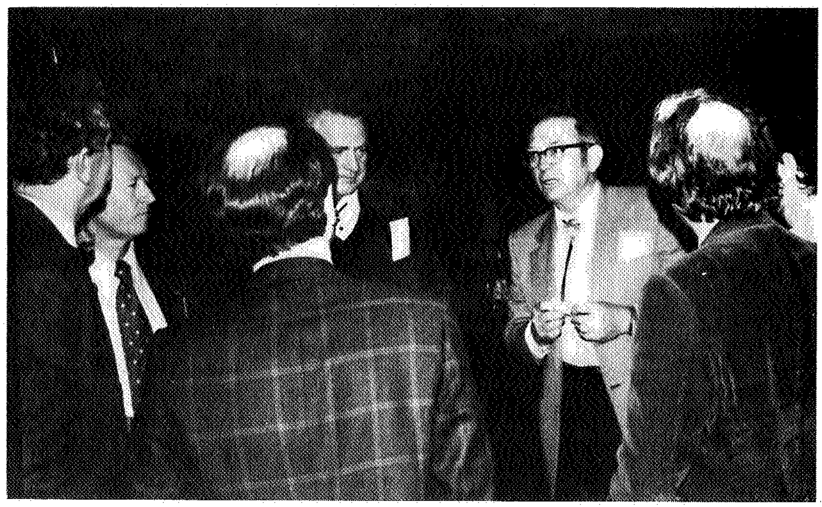
12:15 CONCLUDING REMARKS

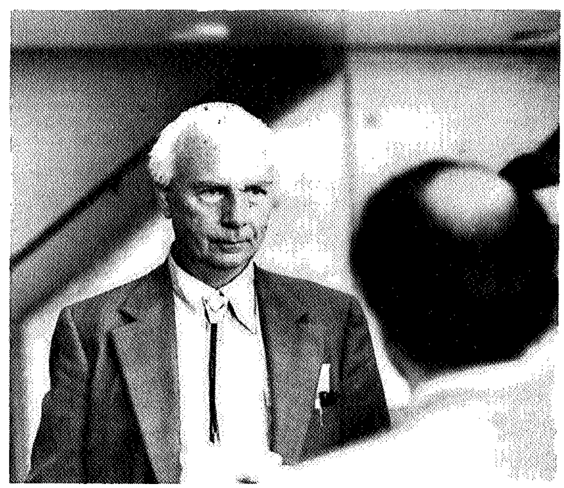
James C. Dodge
Manager
Severe Storms and Local Weather Research Program
NASA Headquarters
Washington, D.C. 20546

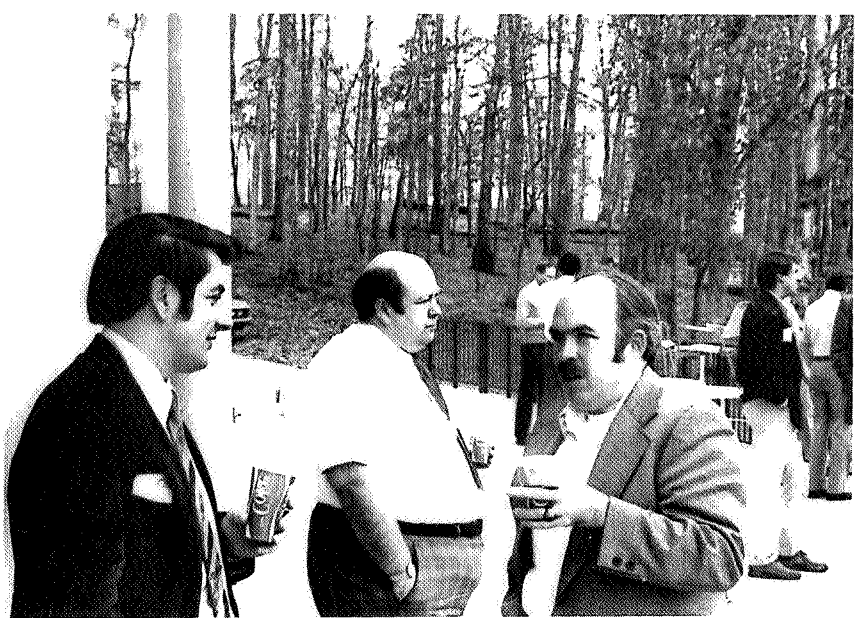


SECTION III

OVERVIEW PRESENTATIONS







LIGHTNING PROPERTIES AND ASSOCIATED EMISSIONS

Marx Brook

New Mexico Institute of Mining and Technology

PART I. INTRODUCTORY REVIEW

A. Introduction. In his book, The Flight of Thunderbolts, B. F. J. Schonland (1964) provides us with a delightful historical narrative which demonstrates how deeply "thunder and lightning" penetrated the religious beliefs and folklore of primitive peoples. Lightning was considered a fearful weapon of the gods, a belief which appears to persist in some measure to this day. Centuries of observation have perhaps dispelled some of the fears, and perhaps man's cumulative familiarity with the event has increased his fascination with it, but our present knowledge of lightning still remains far from complete or adequate. And we are still to this day trying to understand how to avoid lightning damage as each new generation of tall structures and sophisticated devices presents new problems. The Apollo 12 moon rocket was probably the most sophisticated lightning rod ever built. It is appropriate, therefore, that this workshop is dedicated to identifying the contributions which space observations can make to our knowledge of lightning and lightning-related phenomena,

In the time allotted for this talk I shall try to cope with this broad subject by first providing a very brief overview of the lightning observables and environment, and then by taking a selective look at those properties of lightning which might be useful as "space observables." As one might expect for a subject as old as this one, there is an immense literature and folklore associated with it. A few books on the subject are basic and are listed in the references *(2).*

B. The Environment. Lightning discharges are usually associated with convective cloud systems. Most generally these clouds have tops which penetrate well above the freezing level and have been observed occasionally to reach the stratosphere. During the TRIP program at KSC in 1976 one radar echo top reached 62,000 feet. On the other hand lightning has occasionally been reported as originating from clouds whose tops are everywhere warmer than freezing (warm clouds). Also a rare occurrence is the lightning associated with the more violent stages of volcanic eruptions. Recent examples are Surtsey and Heimaey in Iceland, and Sakurajima and Aso in Japan.

The most intense lightning activity in the U.S. appears to occur in the midwest where spectacular lightning displays, tornado funnels and grapefruit size hail often accompany the severe storm systems.

The cellular structure of clouds is inferred from radar studies and time lapse photographs. Lightning appears to be associated with the cloud updraft structure, and hence the spatial extent of lightning channels may be dependent upon cloud cell size. Measurements show a minimum cell size of about 300 - 500 m; cells up to 10 km or larger are often seen by radar.

C. <u>The Location of Lightning Stroke Origins</u>. (a) Ground Strokes. The mechanism(s) by which electric charge is separated in clouds is still a hotly debated issue among researchers and will not be treated here. Recent studies in New Mexico and in Florida indicate that the negative charge brought to earth by a ground stroke is usually located (in summer storms) at a height between 6 and 8 km msl, or at a temperature between -10 and -20°C. Other recent results from the Florida studies indicate that lightning does not usually occur until the radar echo of the growing cloud has reached 9 km or higher. Flashing rates in clouds appear to depend not only upon the cloud echo height but also upon the stage and vigor of vertical development.

(b) Cloud Flashes. The positive electric charges associated with cloud flashes are located higher in the cloud than are the ground stroke charges. The cloud discharge appears to originate near a region of concentrated positive charge and then progress downward toward and involving the region where the negative charges are located. It appears that the two types of discharges--cloud flash and ground flash--originate from distinctly different regions.

D. <u>The Polarity of Clouds and Strokes</u>. Electrically, the thunderstorm may be approximated in zeroth order by a vertically oriented dipole with the positive charge uppermost. The dominant mode of discharge to ground involves the lowering of negative charge to earth, and since the negative charge is closest to ground, the almost exclusive occurrence of negative polarity ground strokes has always been accepted as a reasonable result. Ground strokes which lower positive charge to earth in more than 90% of the stroke events have been reported recently for the Hokuriku winter storms in Japan, and more recently, discharges associated with supercell storms in Oklahoma have been found to involve numerous positive strokes to earth. The Japan storms exhibit a dipolar structure of normal polarity and hence the ground strokes there originate from the upper parts of the cloud. No data on stroke origins are presently available for the supercell storms.

One other rarely occurring positive ground discharge is worth mentioning. Long after normal lightning activity has ceased (-5 to 10 minutes), a positive ground stroke producing thunder for 30 seconds or more (implying long and extensive channels) may occur in a situation which displays no convective activity. This stroke is usually the last flash of the storm, and is possibly associated with the discharge of positive space charge in and around the thundercloud anvil.

The optical radiation intensity, as detected from above a flashing cloud:, will be affected by scattering due to intervening cloud. Other things being equal, an intensity difference between positive and negative strokes may be observable because they originate at different heights inside the cloud.

E. The Measurement of Electric Field Changes. In our discussion of lightning we shall not be concerned with the ambient electric field, either in fair weather or in the thunderstorm environment. We are cognizant of the presence of electric charge throughout the atmosphere and attached to cloud particles, but the only charges we are interested in are those involved in the lightning discharge itself. By definition, the charge which is effectively lowered, raised, or displaced rapidly on the time scale of the lightning events is called the lightning charge. All other charges which remain essentially in place are ignored, since, by the superposition principal, their contribution to the electric field before and after the flash remains constant.

If we set out an insulated flat plate conductor of area A flush with the surface of the earth, a charge Q_1 will be induced on it in the presence of a vertical electric field E_1 such that $Q_1 = \varepsilon_0 A E_1$, where ε_0 is the permittivity of free space. If a lightning stroke occurs involving the removal of an amount of charge $AQ = Q_2 - Q_1$, where Q_2 is the charge remaining in the cloud, a change in electric field, $AE = E_2 - E_1$ will occur such that $AQ = \varepsilon_0 A \Delta E$. If the plate is connected to a charge amplifier as shown in Figure 1, the output voltage change, AV, will be $AV = -\varepsilon_0 A \Delta E / C$, where C is the capacitor which determines the sensitivity. The capacitor is usually shunted with a resistor to provide a time constant which is long compared to the duration of the event under study. For lightning events, three time constants have been found useful: 10 seconds, 3 msec, and 100 psec. The 10 second time constant is useful for observing the entire flash which may last for 0.5 - 1 sec, while the 100 psec time constant is useful for looking at the individual short duration pulses which occur throughout the flash.

F. Photographic Studies, Photographic techniques have been very useful in delineating the multiple event structure of lightning flashes. Leaders, return strokes, continuing currents, and current surges (M components) within the continuing currents were first discovered on photographs. Photographs are also useful in determining leader and return stroke velocities, and have also been used to measure wind shear in the sub-cloud layer.

Figure 2 is a schematic diagram showing a typical sequence of lightning events. In (a) we see a fixed camera picture of the flash. In (b), where time goes from left to right, we see the development of a stepped leader followed by a return stroke. There is then a dark period for about .04 seconds, then a dart leader (faster than the stepped leader) again followed by a return stroke. The dart leader return stroke sequence is repeated once more to complete the 3 stroke flash.

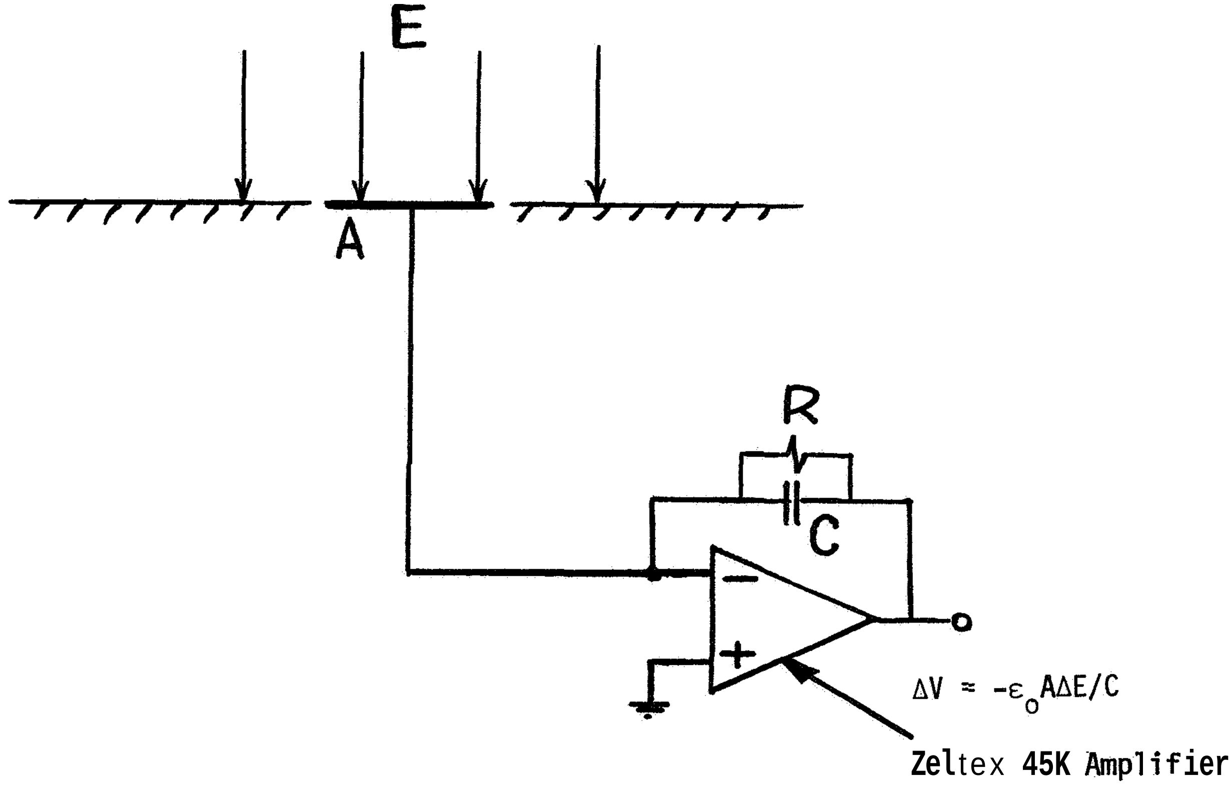


FIGURE 1. FET OPERATIONAL AMPLTFIER USED AS A CHARGE AMPLIFIER FOR MEASURING CHANGES IN ELECTRIC FIELDS PRODUCED BY LIGHTNING FLASHES.

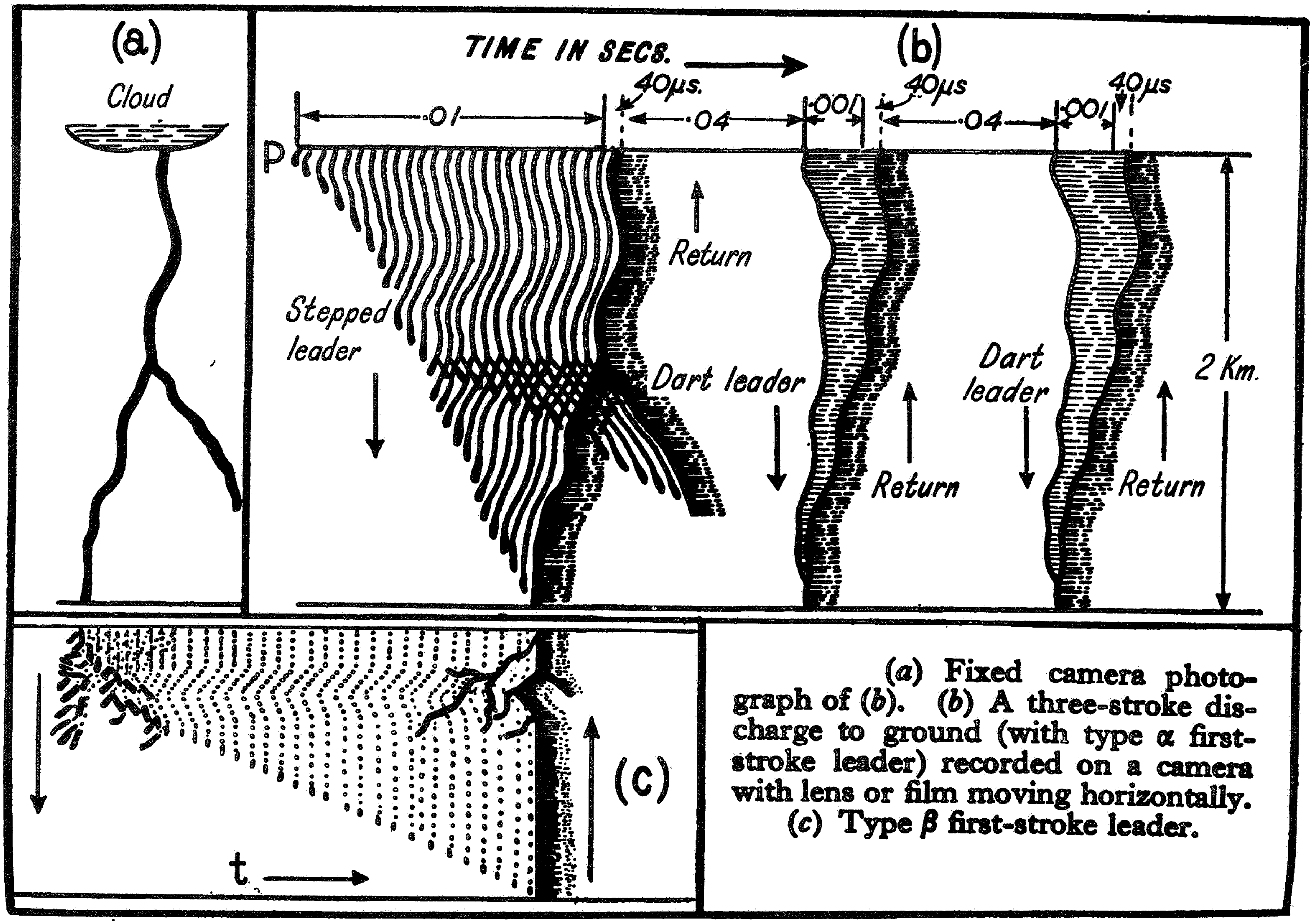


FIGURE 2. SCHEMATIC DIAGRAM OF TYPICAL SEQUENCE OF LIGHTNING EVENTS.

Figure 3 shows the photograph of a lightning flash which consisted of 54 luminosity peaks of which 26 were leader-return stroke combinations. The flash lasted for 2 seconds.

Figure 4 is the moving film camera photo of a similar flash, except that an outstanding feature is the existence of a long continuing luminosity following one of the return strokes.

The next several figures are shown to provide examples of actual stepped leaders, dart leaders, continuing luminosities, and long horizontal air discharges (Figures 5-8).

G. Electric Field Changes. We now return to the field changes produced by lightning flashes. In Figure 9, we show a schematic of the photographic record along with a long and short time-constant record of the electric field. The upper example (a) is that of a discrete flash, i.e., it consists of discrete strokes only, strokes which are not followed by a long continuing current. In (b) we see the field records for a Hybrid flash, i.e., one which consists of both discrete and continuing current strokes. Both flashes were approximately 20 km distant from the meters.

We note that the appearance of luminosity on the photograph is usually accompanied by impulsive electrical activity on the field-change records. In addition, there are numerous pulses on the electrical records for which the camera produces no below-cloudbase images, a fact which implies that these pulses are produced by processes active wholly within the cloud. We should also note the large slow field change which accompanies the continuing luminosity. This change produces a long continuing current to ground, and usually involves much more charge to earth than do the discrete return strokes.

Figure 10 shows the electric field-change records of a flash seen by eight widely separated field-change meters. Of particular interest here are the different polarity deflections between stations viewing the same event. All return stroke deflections are alike and positive, signifying negative charge removed from the cloud. But stations close to the discharge show negative leader deflections, whereas distant stations show small positive or zero deflections.

Figure 11 shows the electric field-change record for a cloud flash as seen by short and long time-constant instruments. The cloud field-changes appear to exhibit specific portions which are characteristic and recognizable in terms of the pulsative activity.

Figure 12 illustrates the large variety of cloud-flash field-change patterns which are encountered as a storm approaches and recedes from the observer.

H. Luminosity Measurements. In addition to photographs, measurements of the luminous characteristics of various lightning events have been made with photoelectric devices. Figure 13 shows several records

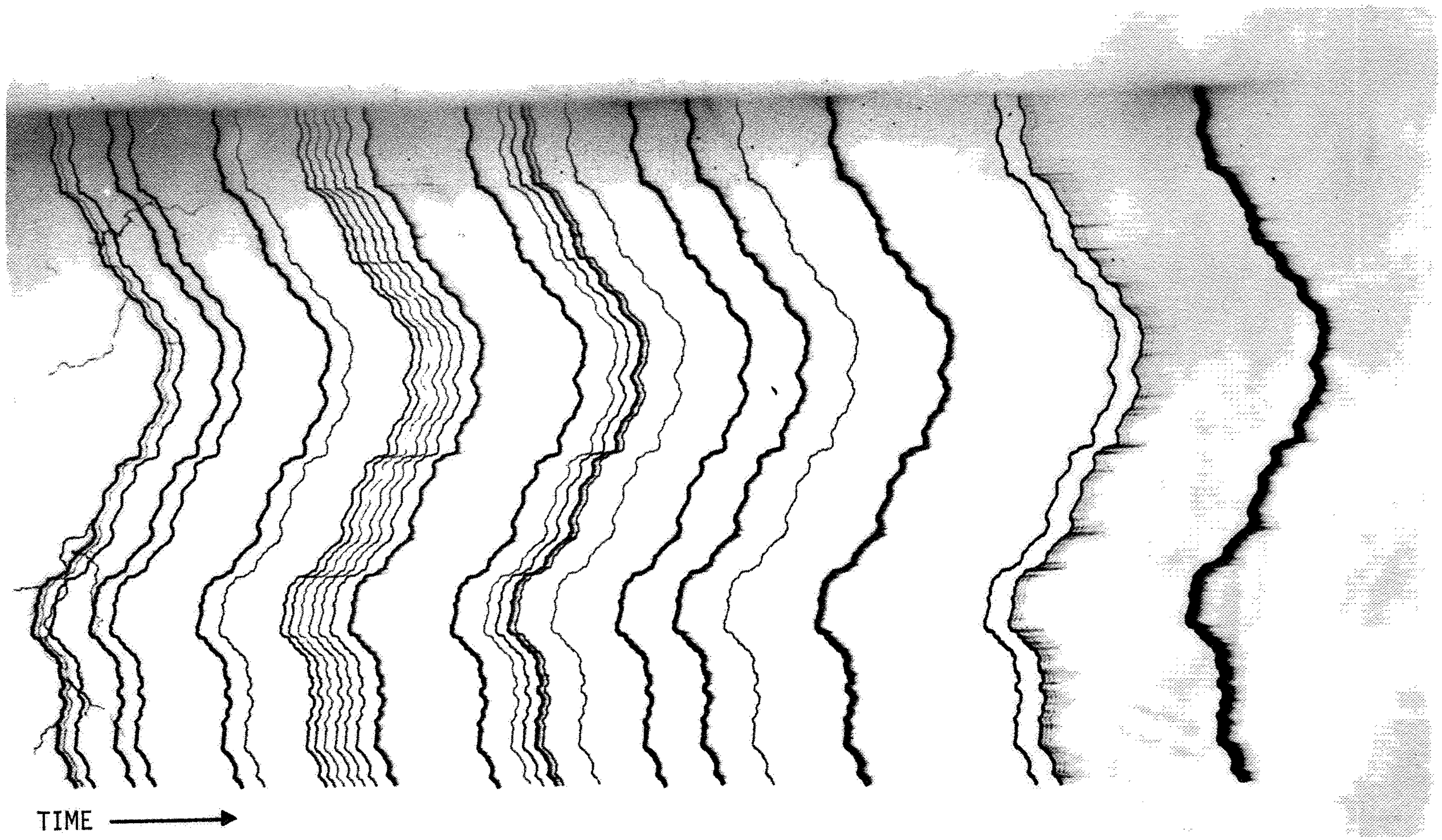


FIGURE 3 MOVING CAMERA PHOTOGRAPH OF A LIGHTNING FLASH (2 SEC DURATION).

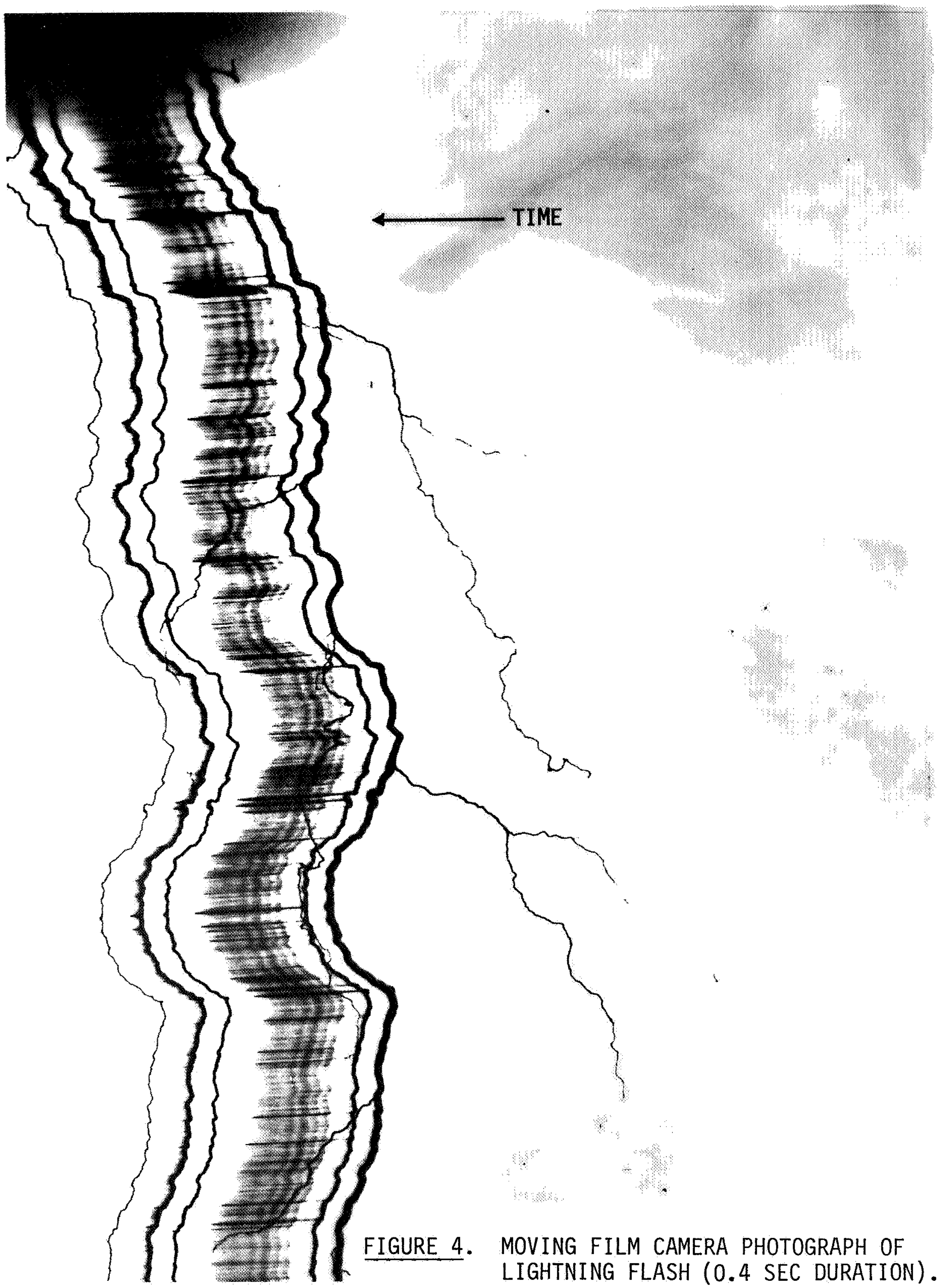


FIGURE 4. MOVING FILM CAMERA PHOTOGRAPH OF LIGHTNING FLASH (0.4 SEC DURATION).

FIGURE 5 FLASH TO GROUND FOLLOWED BY A VERY LONG HORIZONTAL DISCHARGE.

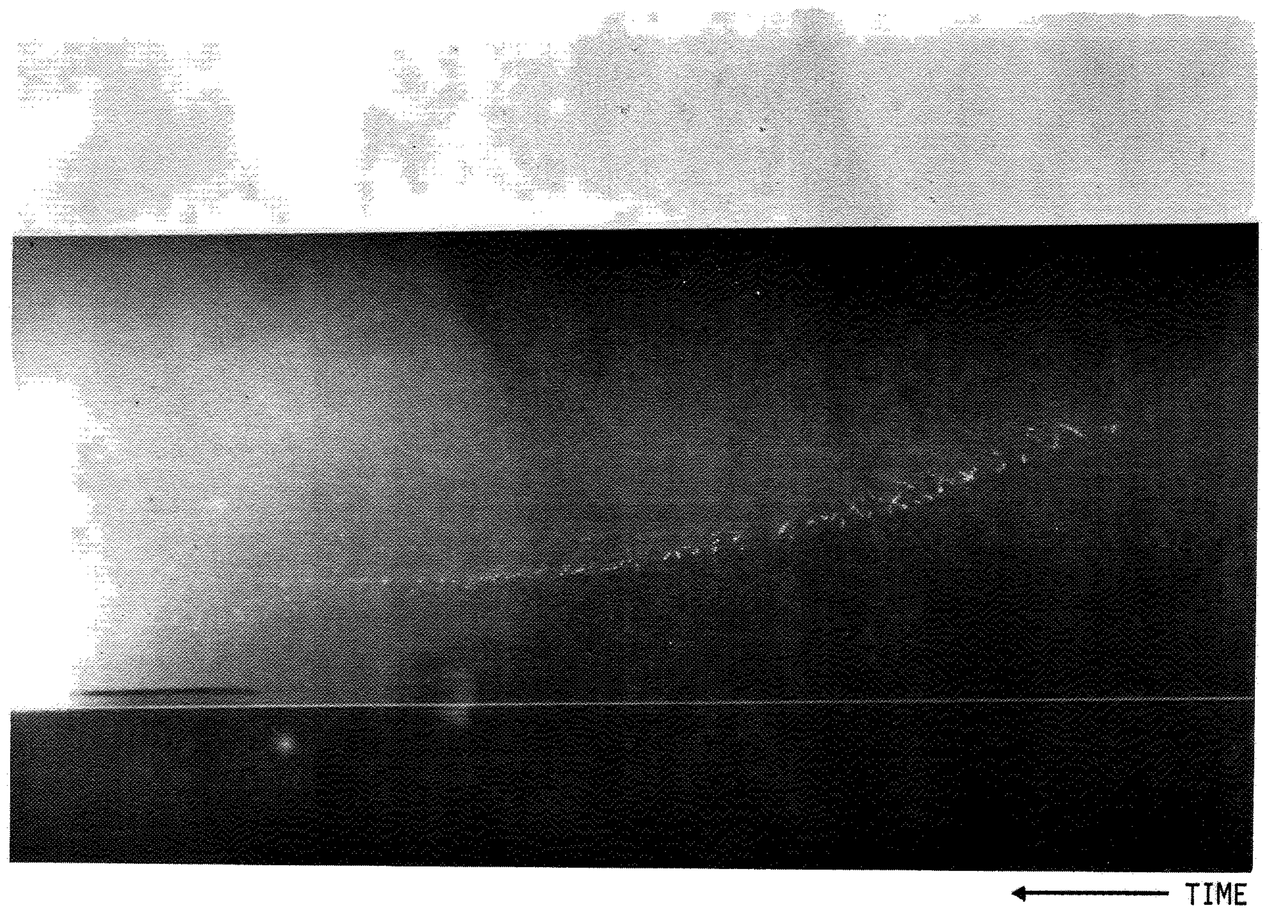


FIGURE 6 STEPPED LEADER

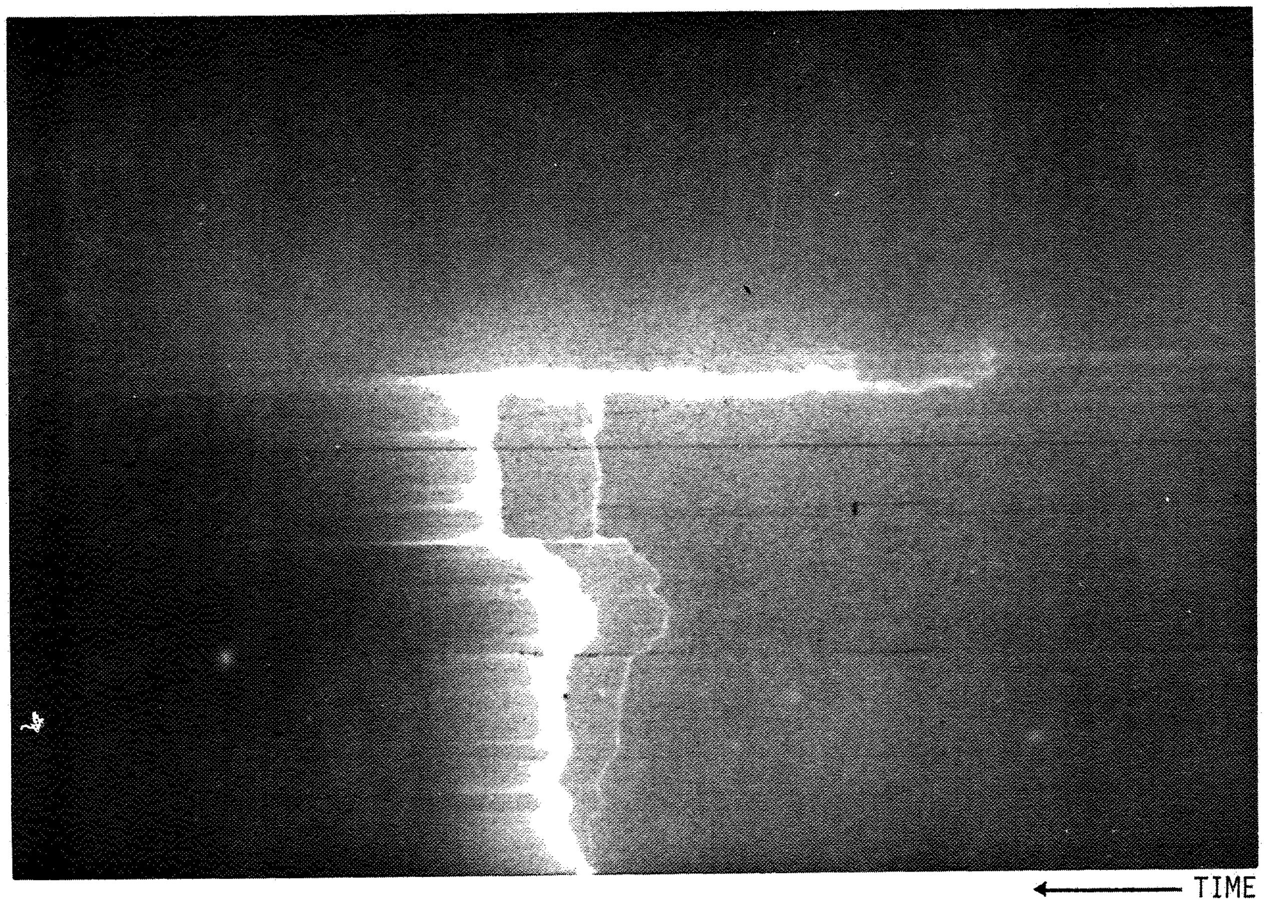


FIGURE 7 DART LEADER PRECEDING A RETURN STROKE

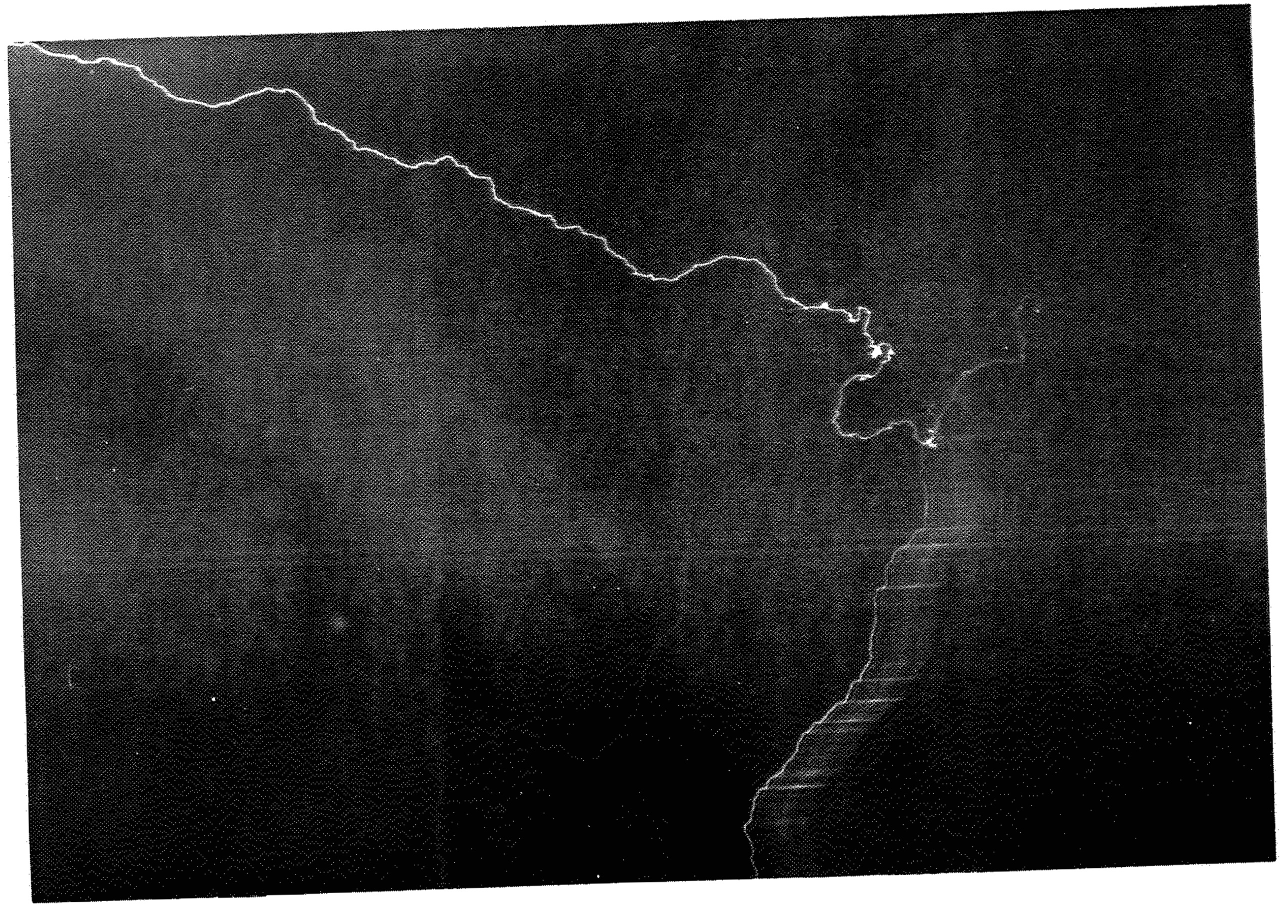
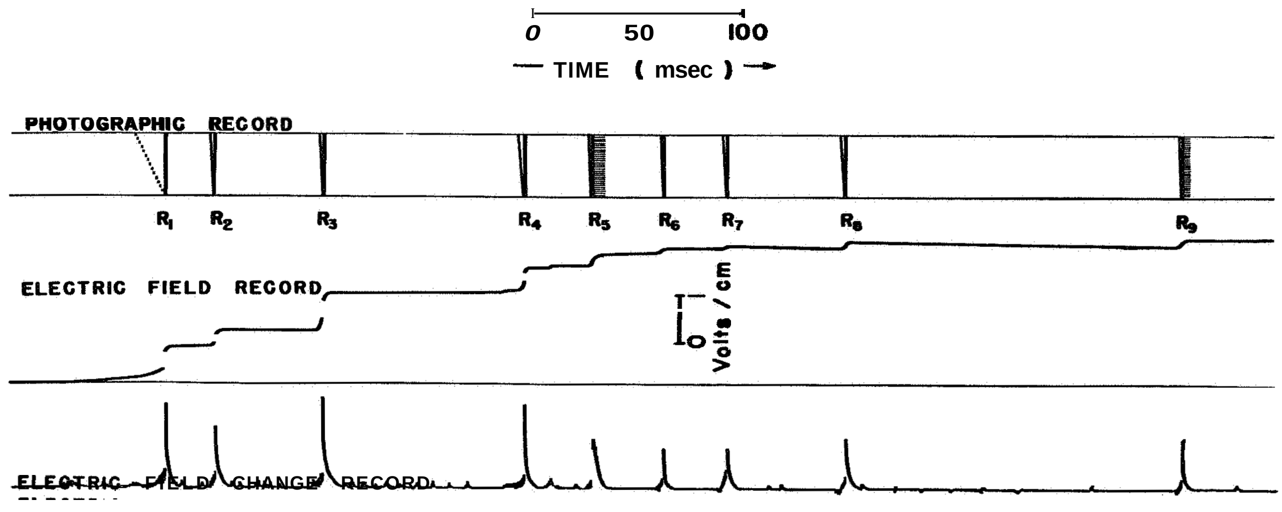
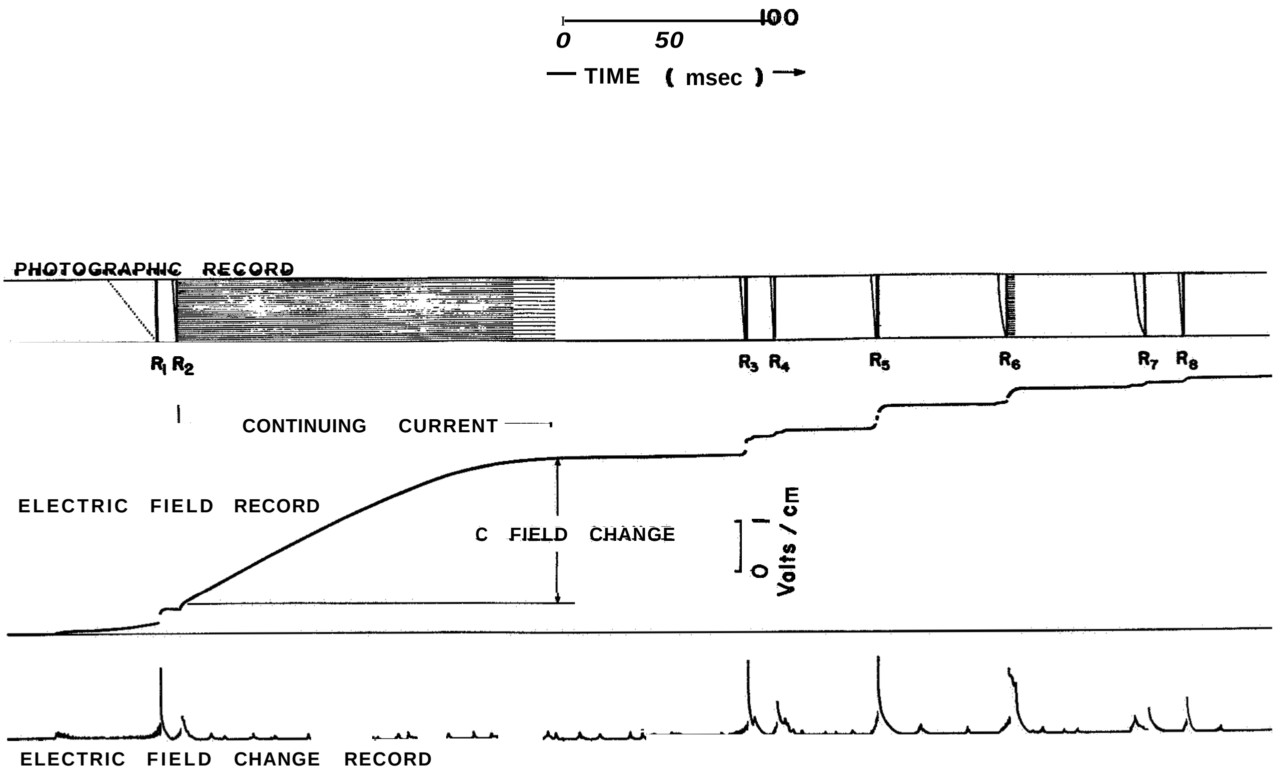


FIGURE 8 CONTINUING CURRENT STROKE TO GROUND



(a) DISCRETE FLASH (Flash No. 109, 19 km Distant)



(b) HYBRID FLASH (Flash No. 106, 20 km Distant)

FIGURE 9. SCHEMATIC OF PHOTOGRAPHIC RECORD AND LONG AND SHORT TIME-CONSTANT RECORD OF ELECTRIC FIELD. (a) DISCRETE STROKES ONLY. (b) HYBRID FLASH, BOTH DISCRETE AND CONTINUING CURRENT STROKES.

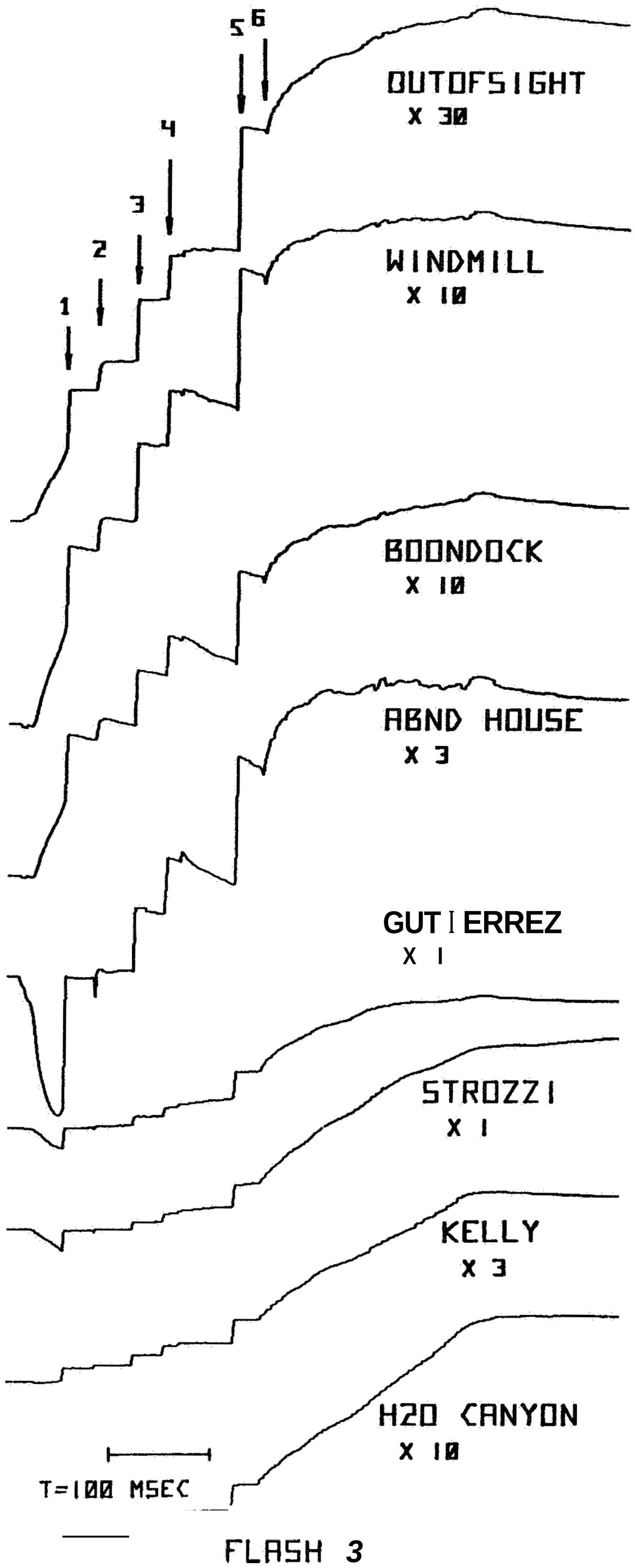
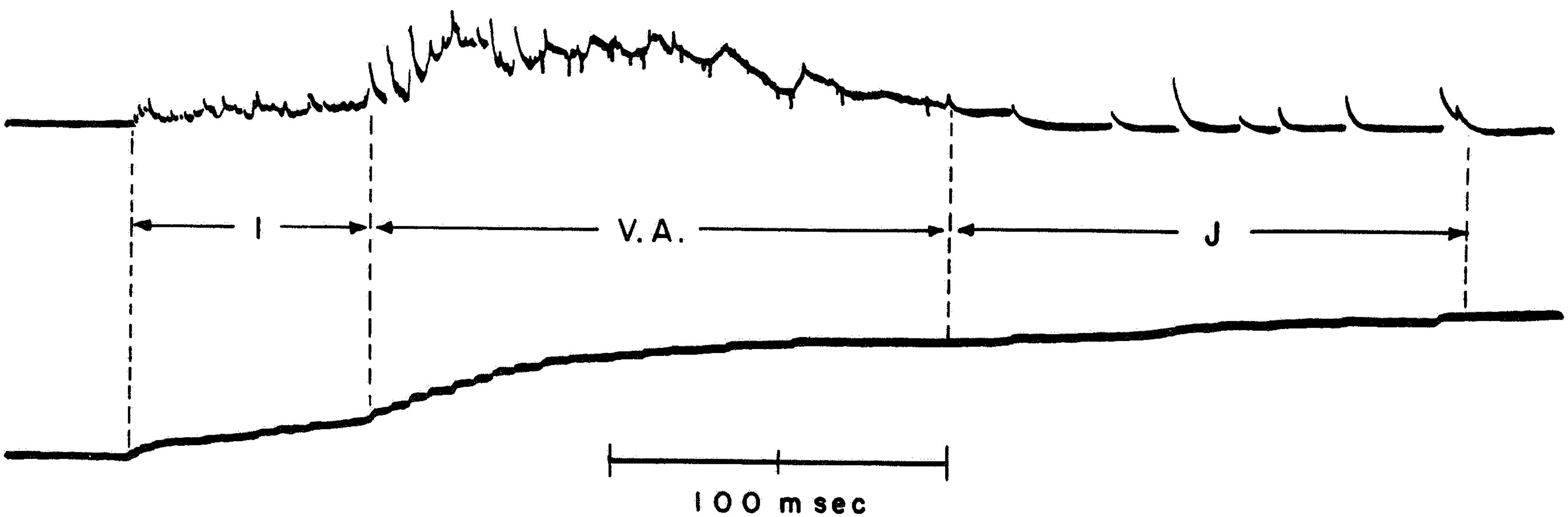


FIGURE 10. ELECTRIC FIELD-CHANGE RECORDS OF A FLASH AS SEEN BY EIGHT WIDELY SEPARATED FIELD-CHANGE METERS.



I: Initial portion, V.A.: Very active portion, J: J-type portion

FIGURE 11 ELECTRIC FIELD-CHANGE RECORD FOR A CLOUD FLASH AS SEEN BY SHORT AND LONG TIME-CONSTANT INSTRUMENTS.

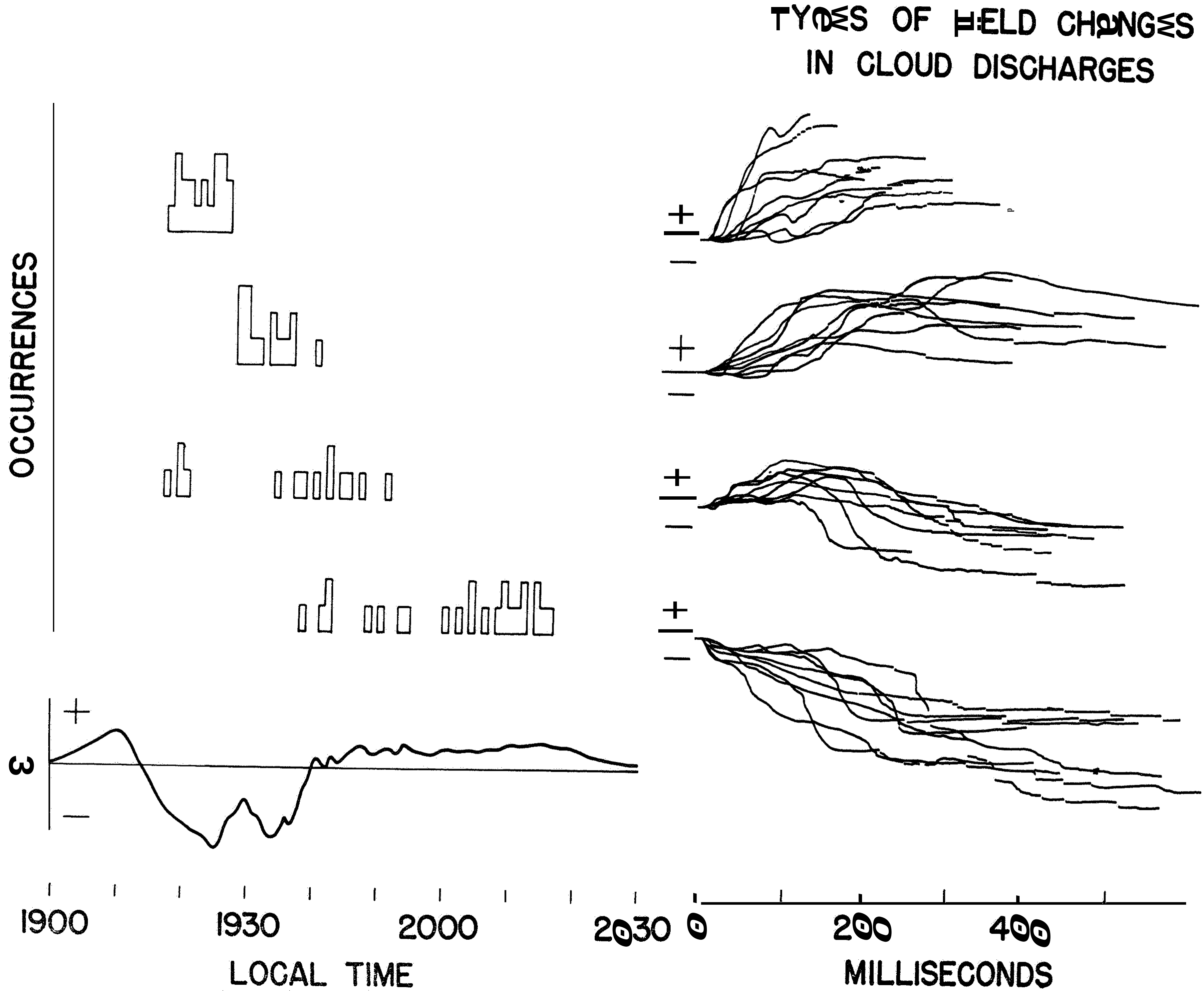
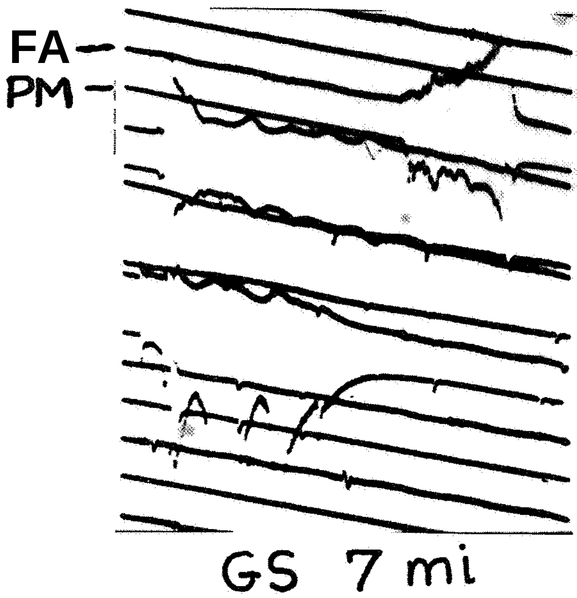
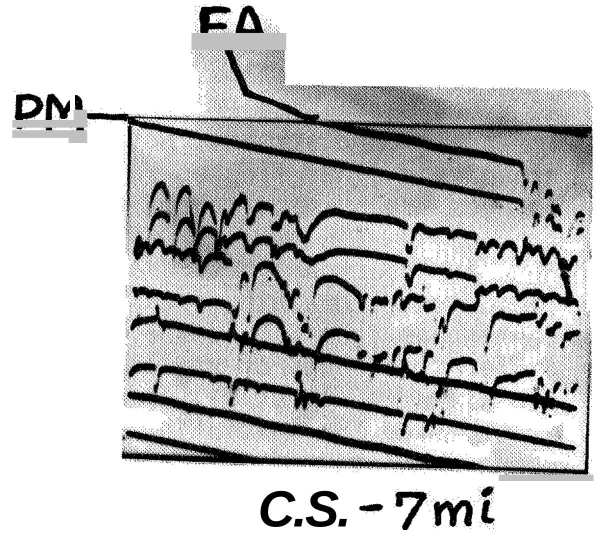


FIGURE 12. CLOUD-FLASH FIELD-CHANGE PATTERNS OF APPROACHING AND RECEDING STORM.





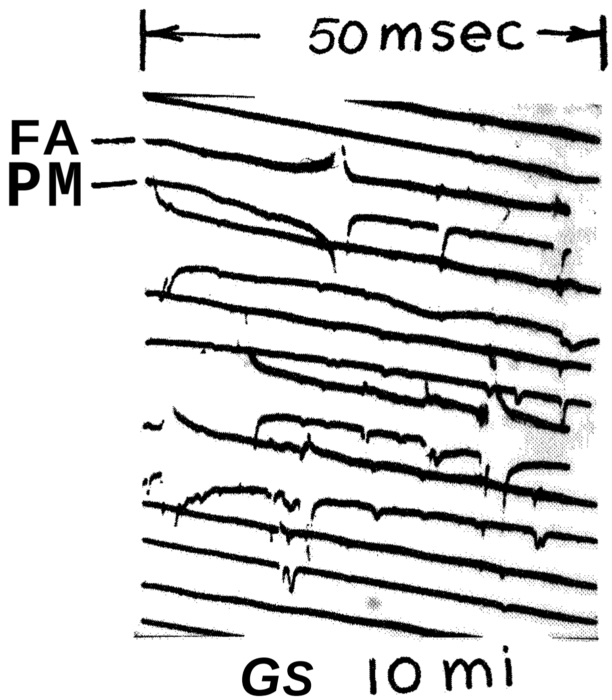


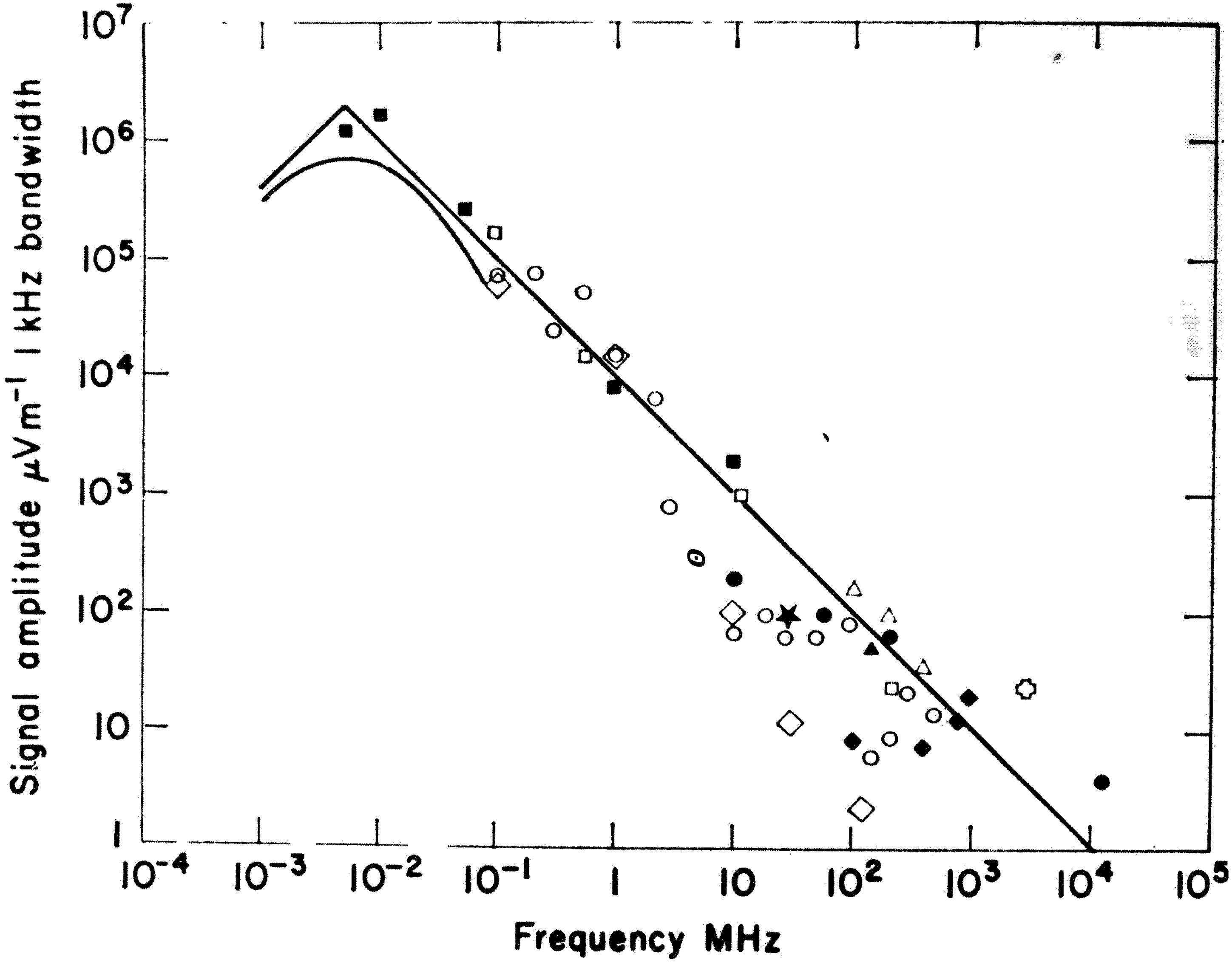
FIGURE 13. LIGHTNING FLASHES RECORDED ON A DUAL BEAM OSCILLOSCOPE SHOWING FAST ELECTRIC FIELD CHANGES (FA) AND LUMINOSITY REGISTERED BY PHOTO MODIFIER TUBE (PM).

of lightning flashes recorded on a dual beam oscilloscope. Time goes from left to right and from top to bottom. The traces are labeled FA, referring to the short time constant electric field meter (in this case RC = 0.5 msec), and PM representing the photomultiplier (optical) output. For the ground strokes, note the "mirror image" response. For both ground and cloud flashes, almost all of the measurable electric field changes are accompanied by detectable luminous emissions.

I. Electromagnetic Radiation. A broad spectrum of electromagnetic radiation accompanies each lightning flash. The spectrum is essentially continuous from ELF to VHF, but the various lightning events produce different amounts of radiation at different frequencies. For example, radiation at almost all frequencies above a few hundred kilohertz accompanies the initiation of a stepped or dart leader, but high frequency radiation (>30 MHz) does not always accompany the return stroke. The maximum power radiated by return strokes is found in the range between 6 and 10 kHz. From about 10 kHz to 50 MHz the signal amplitude (μV/m in a 1 kHz bandwidth) decreases monatonically. Beyond about 50 MHz the amplitude versus frequency characteristics are not yet clearly defined. Figure 14 is a compilation of data on the amplitude spectrum of lightning from 100 kHz to 10^4 MHz. Because the ionosphere does not transmit signals below about 30 MHz, we are concerned primarily with the UHF and VHF spectrum.

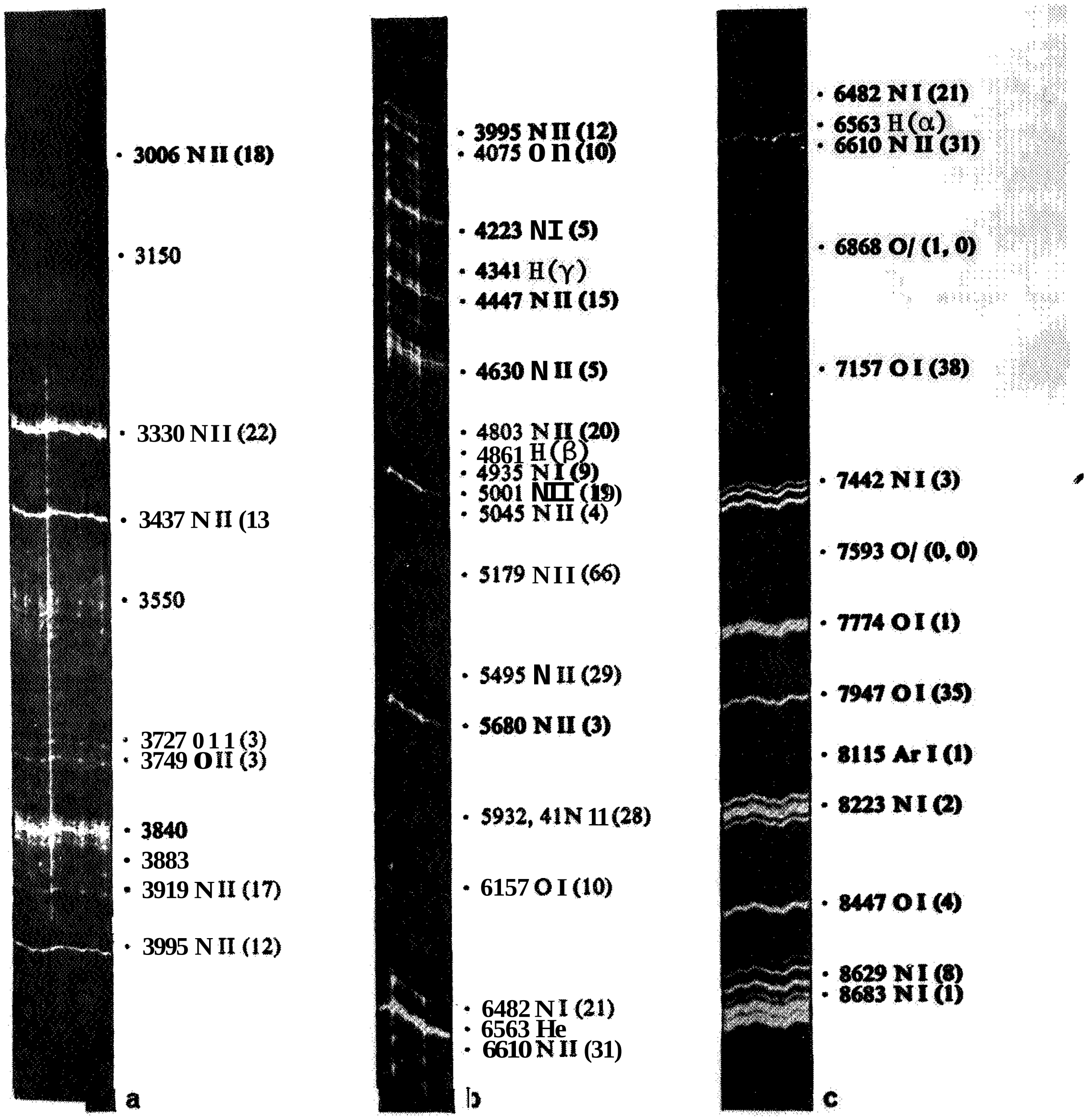
J. The Optical Spectrum of Lightning. The optical spectrum of return-stroke lightning is now well known, due primarily to a revival of the slitless spectrographic technique by Leon Salanave. Figure 15 shows the essential features of the spectrum from the near ultraviolet to the near infrared. These spectra were taken over the full duration of a lightning flash. Time resolved spectra with microsecond resolution, showing both leader and return stroke emissions at a number of wavelengths have been obtained by Orville; photoelectric measurements using narrow bandpass filters were obtained by Krider and by Baresch at Los Alamos. Figure 16 is a reproduction of one of Orville's time resolved spectrums.

In Figure 16, the spectrum of a return stroke, the recorded emissions are due to neutral hydrogen or singly ionized atoms of nitrogen and oxygen. The luminosity rises from zero to peak in less than 10 psec, except for H - *a*, which peaks after about 20 psec. Only one stepped leader spectrum has been published. It is curious that emissions occur in steps only for the NII species. The steps are "superimposed upon a modulating continuum and neutral emissions whose intensity increases with time." The dart leader spectrum has been recorded more often and appears to be devoid of neutral atom emissions. At present, there are no good existing spectra representative of in-cloud discharges.



Peak received amplitude at 10 km for signals radiated by lightning.

FIGURE 14

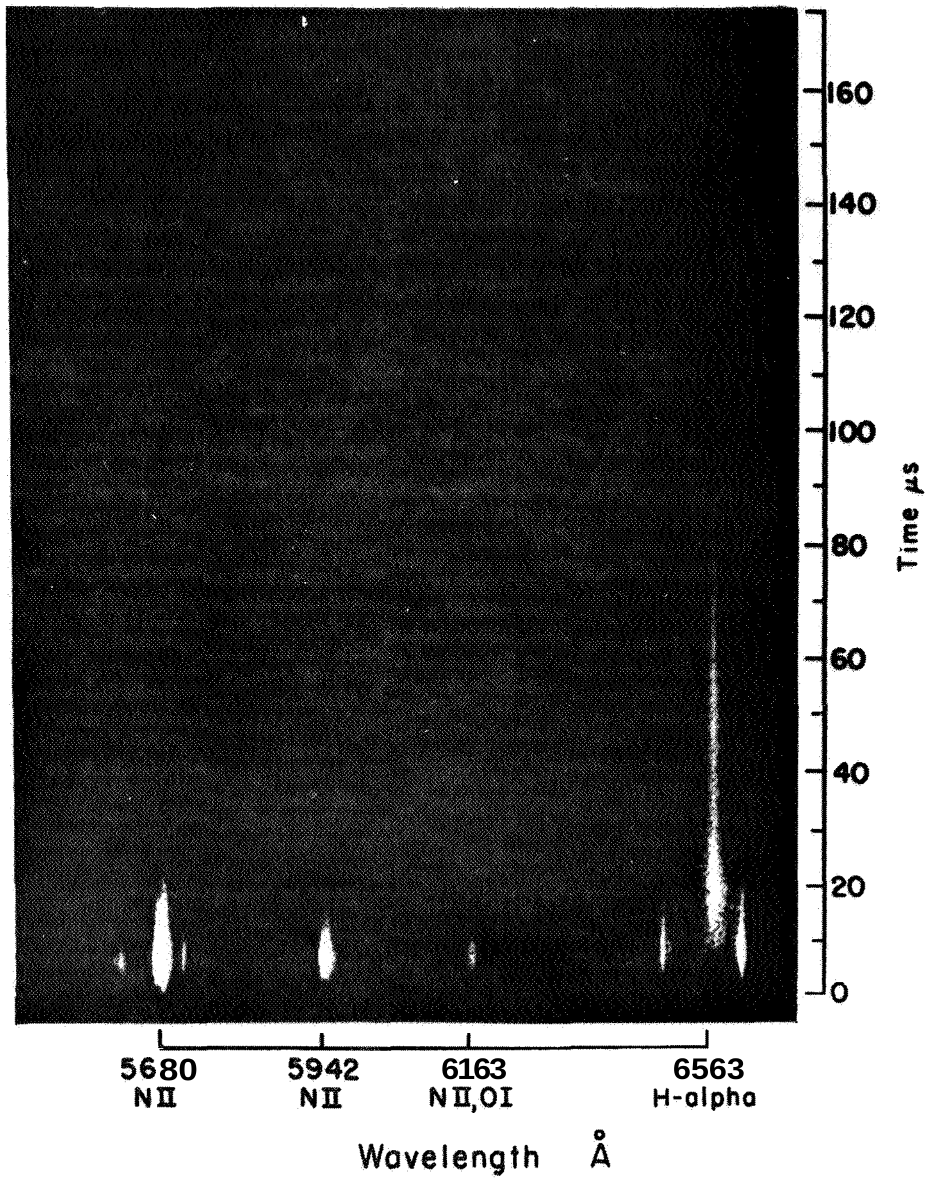


a) The ultraviolet spectrum of lightning obtained on Kodak Plus X film with a transmission grating and fore-prism, both of fused quartz. A Schott UG-5 filter cuts off the unwanted visible spectrum; ozone around the channel and/or in the intervening air path cuts off the atmospheric transmission somewhat below 3,006 Å, as shown by the fading part of the figure (sharp horizontal streak in upper part of picture is a scratch on the film) (Orville and Salanave, 1970).

b) The visible spectrum of lightning, photographed on Tri-X Aerecon film with a slitless spectrograph. The wave-lengths, in ångströms, are only approximate and are merely intended, along with the emitting atom or ion, to identify the source or the principal emitted in cases of a blend. H-beta and H-gamma are weak and greatly broadened by the Stark effect (Orville and Salanave, 1970).

c) The infrared spectrum of lightning obtained on Kodak High-speed infrared film and using the same spectrograph as for Fig. b. The Aero Tessar lens is designed to perform especially well in the red to infrared region, hence the excellent focus over the entire spectrum of H-alpha to nearly 8,700 Å (Orville and Salanave, 1970).

FIGURE 15. ESSENTIAL FEATURES OF SPECTRUM FROM NEAR ULTRAVIOLET TO NEAR INFRARED.



Time-resolved slitless spectrum of a return stroke obtained from a narrow vertical section of the lightning channel with 5 μs resolution. The NII emissions have been analysed for temperature and the H-alpha emission for electron density (Orville, 1968a).

FIGURE 16. SPECTRUM OF A RETURN STROKE.

PART 11. SPACE OBSERVABLES

A. Propagation. In the previous sections we have tried to expose those properties of lightning which might serve for "feasibility" discussions. The electric field-changes which are so vital to the identification and interpretation of lightning events are of no utility as far as space measurements are concerned. We are of course referring to the electric fields here regarded as essentially electrostatic. From the point of view of measurements to be made from a platform above the ionosphere, not only are the static fields of no importance, but radiation fields for frequencies below about 20 MHz are also essentially useless because propagation through the ionosphere is highly attenuated and unreliable. The forms of energy to be detected are therefore limited to optical signals and to radio wave signals above ~30 MHz. In what follows we use the electric field-changes as a reference point for relating radiation to its source event.

B. Source Signal Strengths. The optical signals originating from return strokes are by far the most intense and most easily identifiable. The best available optical ground measurements for the various lightning events are given by Baresch (1970). Table 1 gives the incident peak spectral irradiances ($W cm^{-1}$ $Å^{-1}$) for eleven optical pulses originating from a ground flash 27.4 km distant. The irradiances in the table are given for two wavelengths, and were measured with collimated photometers equipped with appropriate interference filters. Baresch has also measured the distance dependence of the irradiance, and has expressed it as the ratio of 6563Å/3914Å. These data are reproduced in Figure 17.

Most important for our purposes are the source characteristics expressed as spectral intensities, I, ($W, sr^{-1}, Å^{-1}$). The relative spectral intensities produced by lightning are given for four wavelengths in Table 2.

The most probable spectral intensity at 3914Å is given by Barasch as ~$10^4 W sr^{-1} Å^{-1}$. The distribution function for the 3914Å spectral intensities is shown in Figure 18. Figure 19 shows the distribution functions for four wavelengths relative to 3914Å.

In a parallel study at Los Alamos, T. R. Connor (4) provides quantitative data on time-resolved slitless lightning spectra of first and subsequent return strokes, continuing current strokes, the spectrum of a single return stroke at three different heights along the channel, all correlated with the electric field data. A summary of his results follows.

1. First Return Strokes. The strong line features are those of NI, NII, OI, and HI, and there are no molecular band-heads (unlike the photometer and the slit spectrograph results). Almost invariably, the time integrated flux (ergs $Å^{-1}$ cm^{-2}) at 6563Å is less by a considerable factor than at 5000Å and between 4000Å and 4300Å (NII lines).

TABLE 1

INCIDENT PEAK SPECTRAL IRRADIANCES FOR PULSES IN THE SAME FLASH, 27 km DISTANT

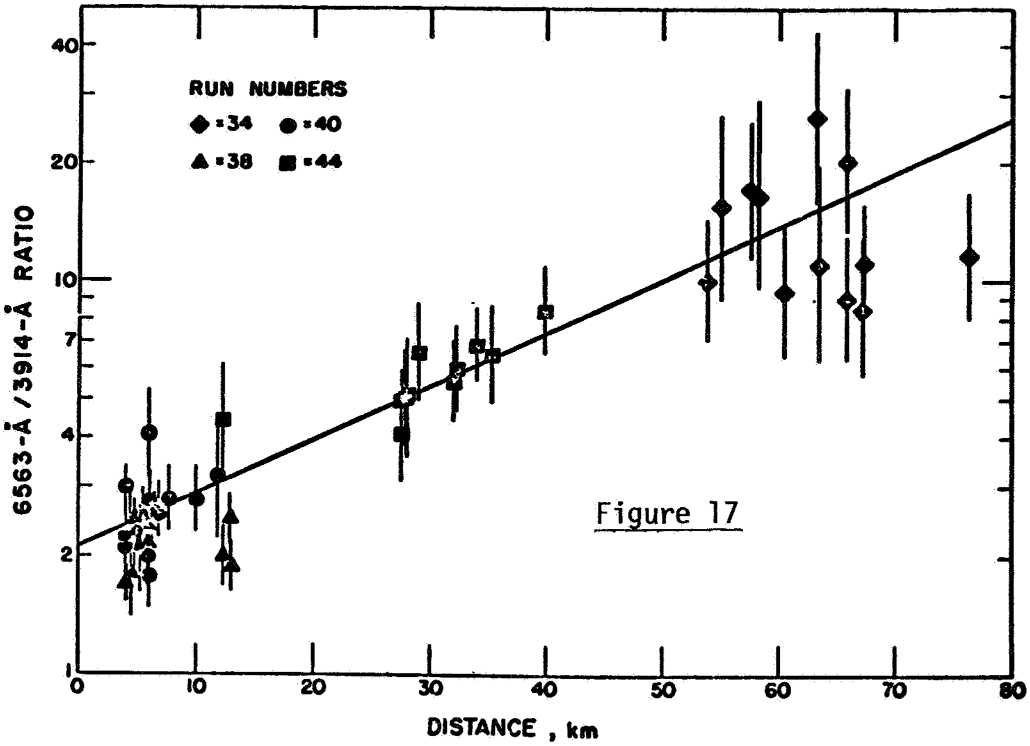
Time msec	Event	Spectral Irradiance 3914 Å $W\ cm^{-2}\ Å^{-1}$	Spectral Irradiance 6563 Å $W\ cm^{-2}\ Å^{-1}$
-009	(a) 1L	2.0×10^{-12}	7.8×10^{-12}
000	(b) 1RS	1.1×10^{-10}	5.7×10^{-10}
040	(c) SRS	1.3×10^{-10}	4.8×10^{-10}
060	---	1.1×10^{-12}	4.9×10^{-12}
077	(d) K	2.1×10^{-12}	1.3×10^{-11}
095	(c) SRS	1.6×10^{-11}	1.1×10^{-10}
096	(c) SRS	6.4×10^{-12}	4.3×10^{-11}
125	(c) SRS	2.5×10^{-11}	1.4×10^{-10}
126	(c) SRS	1.2×10^{-11}	8.6×10^{-11}
141	(d) K	4.0×10^{-12}	1.9×10^{-11}
168	(c) 1'RS	9.7×10^{-11}	6.2×10^{-10}

Legend
1L = First Leader
1RS = First Return Stroke
SRS = Subsequent Return Stroke
K = K - Change
1'RS = A New Channel 1RS

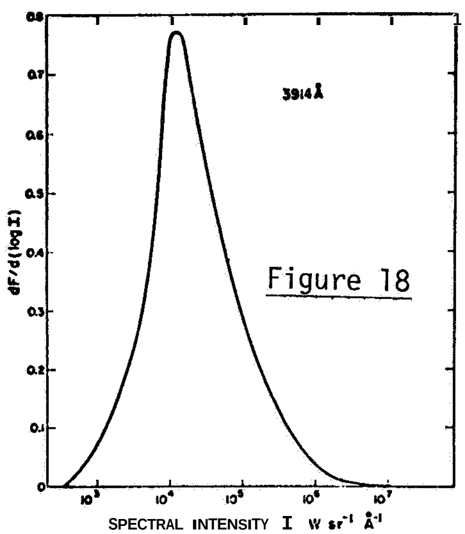
TABLE 2

SPECTRAL INTENSITIES RELATIVE TO 3914Å

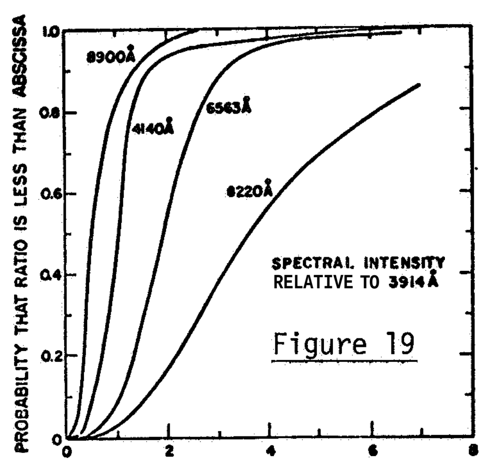
Spectral Feature	Wavelength, Å 13194	4140	6563	8220
All Pulses	1	1.2 ± 0.5	2.1 ± 0.8	4.8 ± 2.8
Samples/Storms	-	409/2	842/4	482/3
First Return Strokes	1	1.0 ± 0.2	1.2 ± 0.3	1.5 ± 0.6
Samples/Storms	-	12/2	26/4	30/3



Distance dependence of incident 6563-Å/3914-Å spectral-irradiance ratio. Each point is the average of all pulse ratios observed for a single flash. The equation of the straight line is RATIO = 2.1 exp(0.031 x DISTANCE), giving an average ratio of 2.1 at the source and a difference of extinction coefficients of 0.031 km^{-1}.



Distribution function, $dF/d(\log I)$, for 3914-Å spectral intensities, I. Logarithms are to base 10. Fraction of pulses with intensities between I_1 and I_2 is $\Delta F = \int_{\log I_1}^{\log I_2} \frac{dF}{d(\log I)} \, d(\log I)$.



Distribution functions of spectral intensities at 4140, 6563, 8220, and 8900 Å, relative to 3914 Å.

2. Subsequent Return Strokes. The same atomic emissions are present as for first return strokes, and also with no molecular bandheads present. The strongest feature, in almost every case, is Ha at 6563. The next strongest feature is NII at 5000Å, but it is not, on the average, much stronger than the multiplets between 4000 and 42508. The degree of ionization is lower than in first return strokes, but higher than in the continuing currents.

3. Continuing Currents. The major atomic line features are due to the neutral NI, OI, and HI emissions, with very weak NII. The strongest line feature in every case is Ha at 6563Å.

Connor's spectra cover only the range out to 6900Å, and do not, therefore, give us any values for the 82208 emissions seen by Baresch on his photometers. The spectral intensity ratio 8220/6565 is about 2/1 (Figure 19) and could be important in sensor considerations.

4. Energy Conversion Efficiency. Of considerable interest to the satellite observation problem is the ratio of the electrical energy deposited to the visible energy radiated by the return stroke. The following table is a summary of Connor's measurements.

TABLE 3

CALCULATION OF EFFICIENCY

Stroke Type†	Range (km)	Rain Transmission	Visible Energy* (joules/meter)	Energy (joules/meter)	(E)
1RS	10.0	8.7×10^{-3}	2.0×10^{3}	3.3×10^{5}	6.1×10^{-3}
SRS	7.0	3.6×10^{-2}	5.6×10^{2}	5.1×10^{4}	1.1×10^{-2}
SRS	7.0	3.6×10^{-2}	4.2×10^{2}	4.0×10^{4}	1.1×10^{-2}
SRS	7.0	3.6×10^{-2}	5.7×10^{2}	9.0×10^{4}	6.4×10^{-3}
1RS	7.2	3.3×10^{-2}	2.3×10^{2}	3.2×10^{4}	7.3×10^{-3}
1RS	4.6	1.1×10^{-1}	2.2×10^{2}	2.1×10^{4}	1.1×10^{-2}
1RS	4.0	1.5×10^{-1}	5.9×10^{1}	2.2×10^{4}	2.6×10^{-3}

Extinction Coefficient Due to Rainfall = 0.475 km^{-1}.

Weighted Average Efficiency = 0.007 ± 36%.

† IRS = First Return Stroke; SRS = Subsequent Return Stroke

* Corrected for (1) humid-air transmission and (2) estimated rainfall transmission.

C. Radio Noise Emissions from Return Strokes. A composite plot of measured radiation field strengths at frequencies from 100 kHz to 10^4 kHz was given in Figure 14 (Pierce, 1977; see also Oetzel and Pierce, 1969). Signal strength measurements from different investigators are in agreement up to about 10 MHz; beyond that there is a spread in values of about 2 orders of magnitude. Table 4, also from Pierce, lists calculated field strengths which are to be expected at satellite altitudes.

TABLE 4

FIELD STRENGTHS AT SATELLITE ALTITUDES
($\mu V m^{-1}$ in 1 MHz Bandwidth)

	Altitude 1,000 Km Frequency			Altitude ~100,000 Km Frequency		
Source	10 MHz	30 MHz	100 MHz	10 MHz	30 MHz	100 MHz
Individual Lightning Flash	2×10^3	5×10^2	10^2	20	5	1
Cosmic Noise Background	10	10	6	10	10	6

Table 4 predicts easily measured signals at orbiting satellite altitudes. For synchronous orbits, the table is pessimistic. Caution should be used in accepting the numbers listed, especially those for frequencies beyond 50 MHz. Additional measurements to supplement those plotted in Figure 14 should be forthcoming soon as a result of the TRIP program.

Some examples of the radiation accompanying ground flashes are shown in Figures 20, 21, and 22. The radiation is shown along with electric field change and optical sensor records. Our caution regarding the data in Figure 14 is based upon records such as Figure 20, which show that the largest radio emissions do not always accompany the return stroke. In Figure 20, the 2200 MHz signal shows a large pulse accompanying the return stroke, whereas for the 50 and 283 MHz radiation the leader radiates far more energy. Especially interesting is Figure 21 where we note large optical pulses corresponding to the five return strokes, but only two strokes which produce radiation at 50 MHz. Generally, radiation accompanies leaders and first return strokes, but subsequent strokes are not always productive of strong radiation pulses.

In Figure 22 we show the emissions accompanying a continuing current stroke. Here the leader produces strong radiation, but the return stroke radiation is absent at 50 MHz and present at 283 and 2200 MHz. The optical signals were recorded on FM channels which provide a DC to 400 kHz response. The other radiation signals were recorded on direct channels, hence the resulting undershoot.

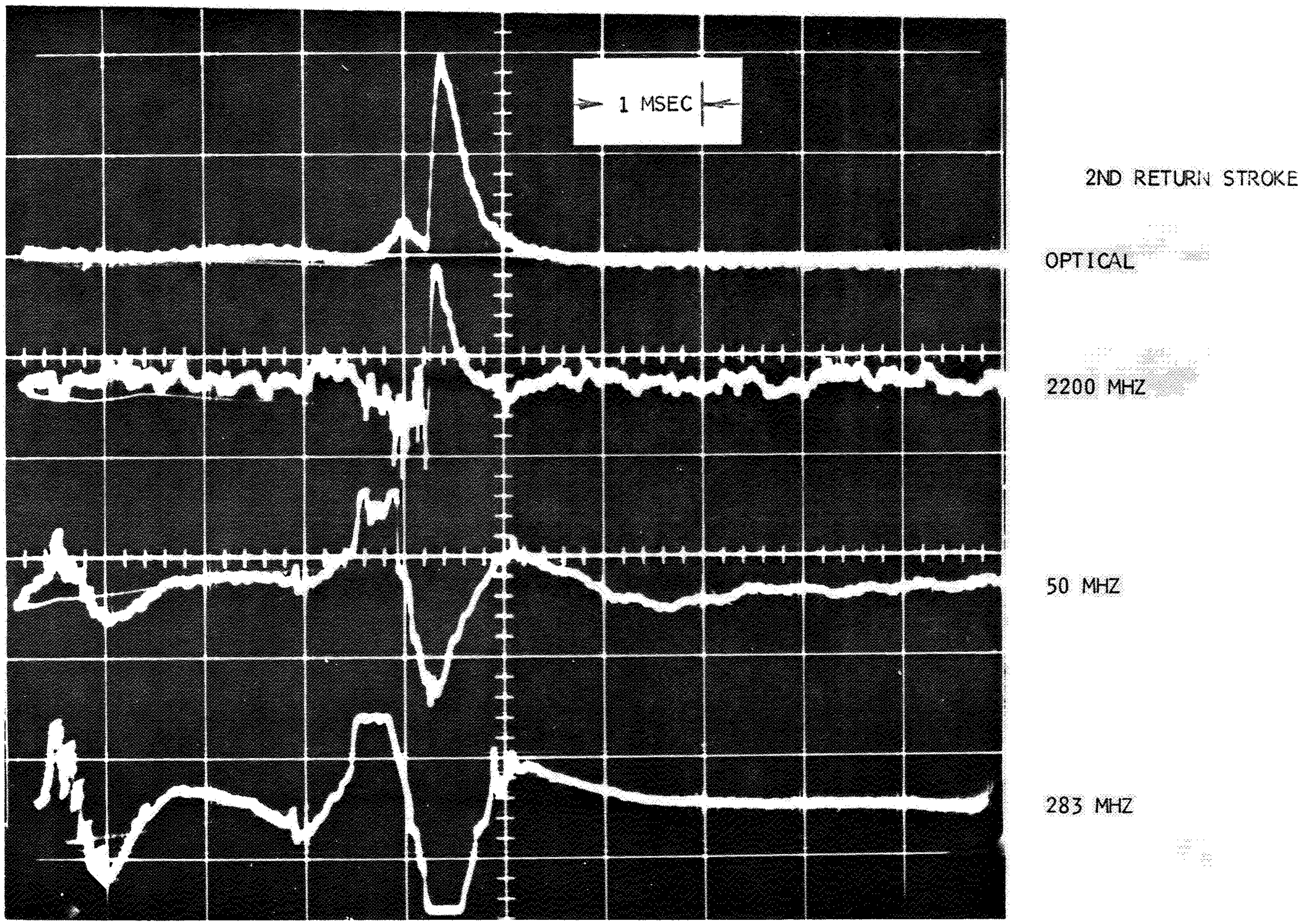


FIGURE 20 RADIATION ACCOMPANYING GROUND FLASHES.

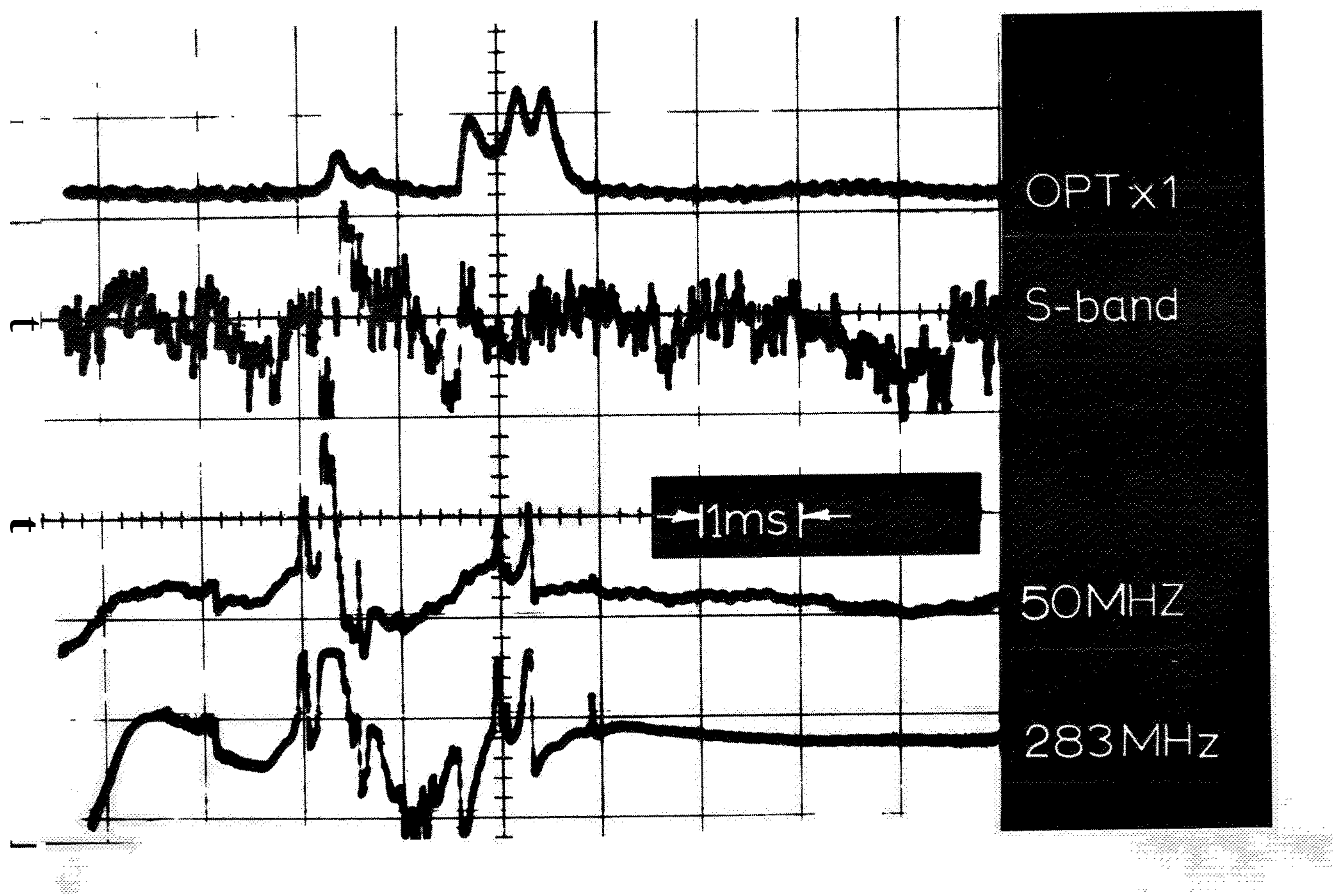


FIGURE 21. RADIATION ACCOMPANYING GROUND FLASHES

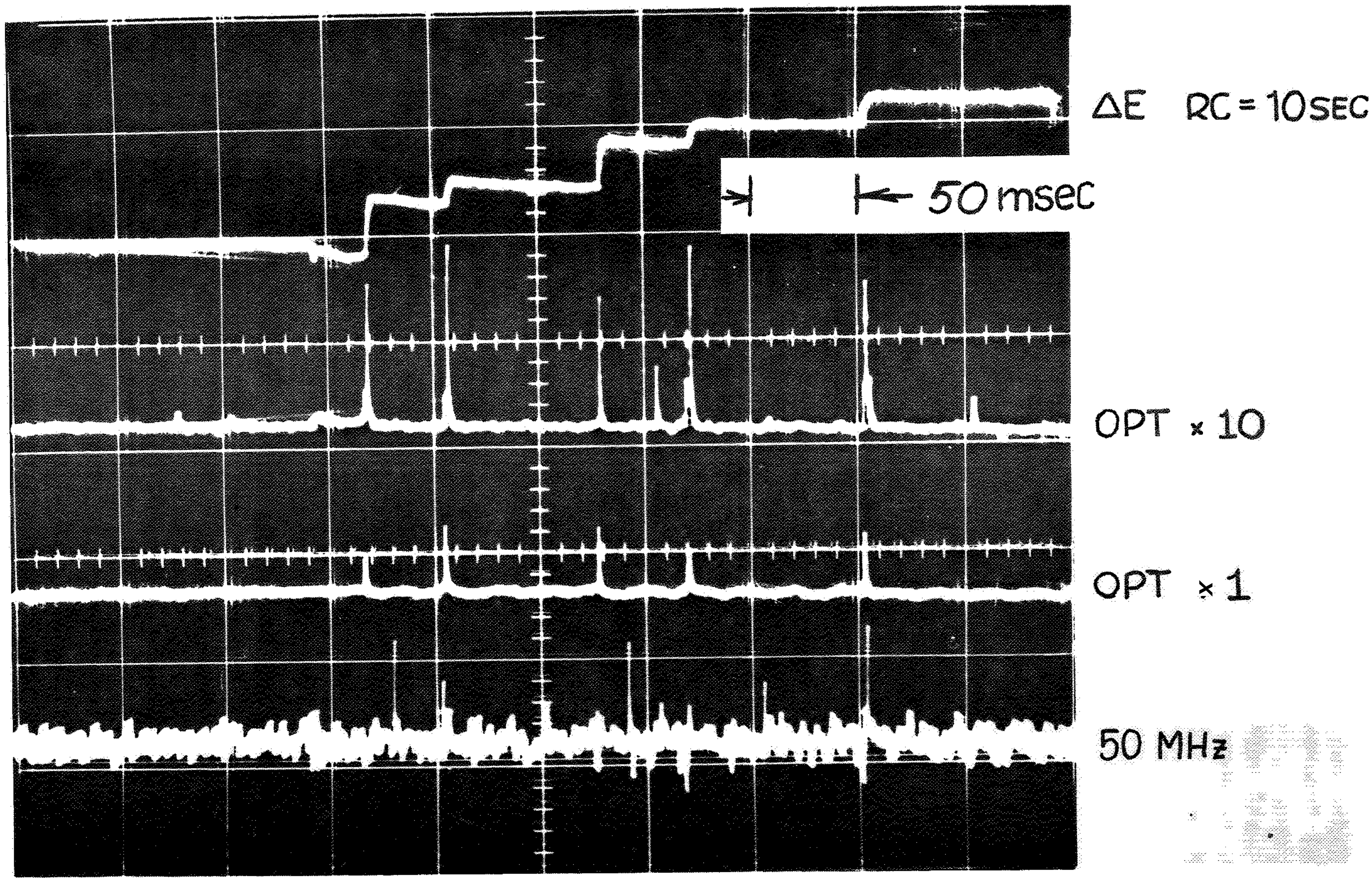


FIGURE 22. RADIATION ACCOMPANYING GROUND FLASHES

Risetimes for the optical signals from return strokes are usually less than 100 psec. Risetimes for the radio signals are much faster, generally less than 10 psec for receivers having bandwidths greater than 1 MHz.

Radio emissions accompanying cloud flashes are shown in the next several figures. In Figure 23 we see that the emissions do not always correspond to the largest field changes. Figure 24 is an expanded view of a small section of the same flash. The risetime of the two optical pulses is about 20 psec. Similar risetimes are seen for the 283 MHz and the 50 MHz signals. Figure 25 shows a typical K-change pulse; the same pulse is shown with a 10 X expanded time scale in Figure 26. The optical pulse has a duration of about 80 μsec. These K-pulses appear near the end of the flash.

Krider, et al. (1965) have observed trains of regularly spaced pulses produced by cloud discharges. The amplitudes of these pulses appear to be small and are not associated with the K-changes. Very little other published work on radiation from cloud flashes in the appropriate frequency range is available at present.

D. <u>Discriminating Between Cloud and Ground Flashes</u>. On the basis of the data reviewed, the optical signals present the greatest promise for both lightning detection and for discriminating between cloud and ground flashes. The difference between the spectra of return strokes and leaders has been noted. Because of the large difference in the current which flows in a ground stroke and in an in-cloud event, a promising approach would appear to be that of spectral comparison. As emphasized earlier, however, no spectra from cloud flashes are presently available.

As regards the location of lightning sources from satellites, it again seems that optical methods are preferable to radio direction finding measurements because of the higher resolution achievable with simpler systems. At this stage, however, all methods should be examined carefully.

In conclusion, I would like to mention that satellite observations of electrical activity accompanying severe storms, in particular the tornadic activity, is highly desirable. Taylor at NOAA and Stanford at Iowa State have made ground-based measurements which should be of great value in designing satellite systems for use specifically in this area.

One last point should be made. Although this talk was not meant to extoll the virtue of any particular scientific or operationally important objective, I want to mention the problem of lightning from warm clouds. This phenomenon is presently regarded as rare, but it may only be "rarely" observed because it occurs primarily in clouds over the ocean. A satellite lightning detector, coupled with infrared measurements of cloud-top temperatures, would serve to answer the warm cloud questions directly and with dispatch.

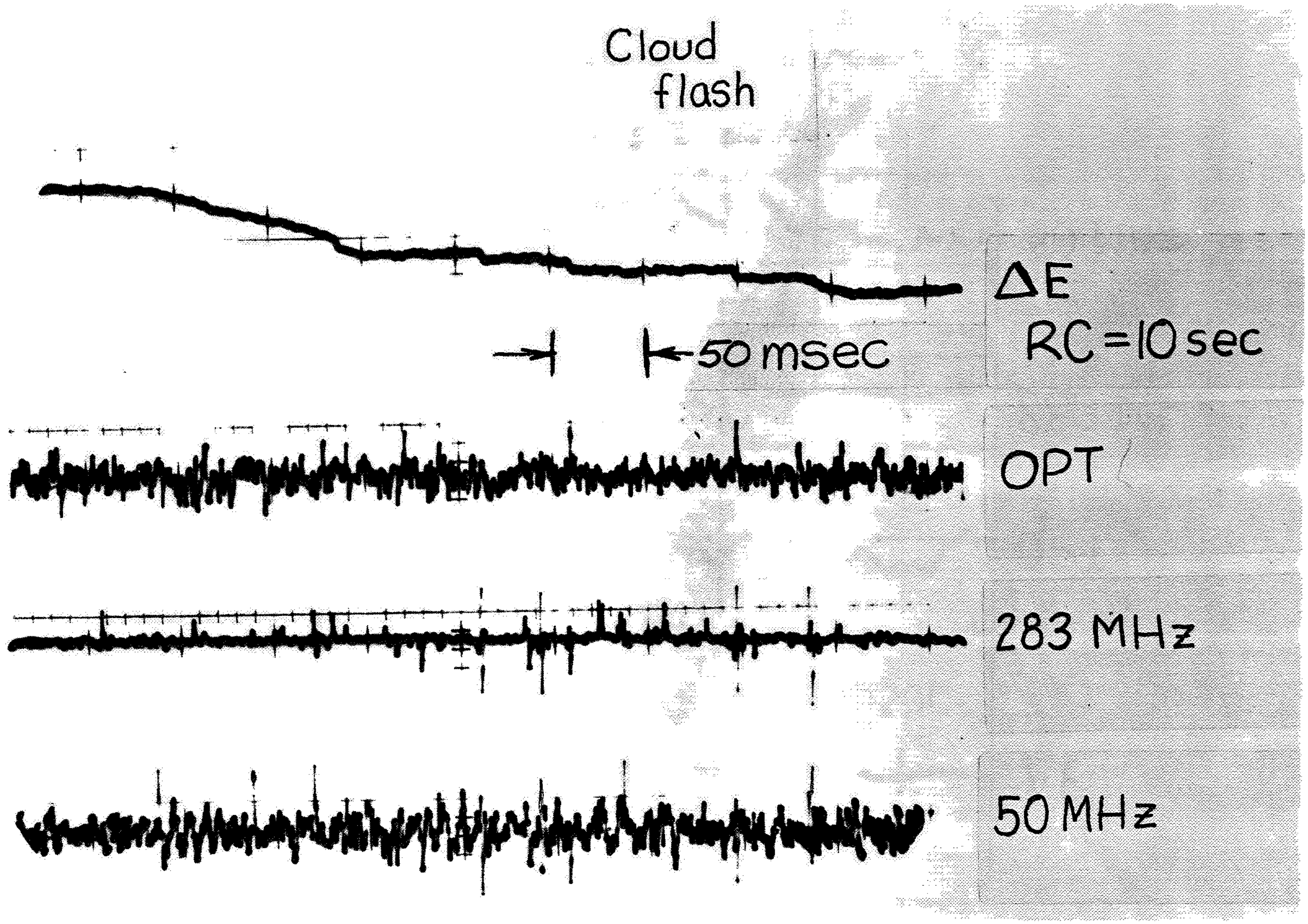


FIGURE 23 RADIO EMISSIONS ACCOMPANYING CLOUD FLASHES.

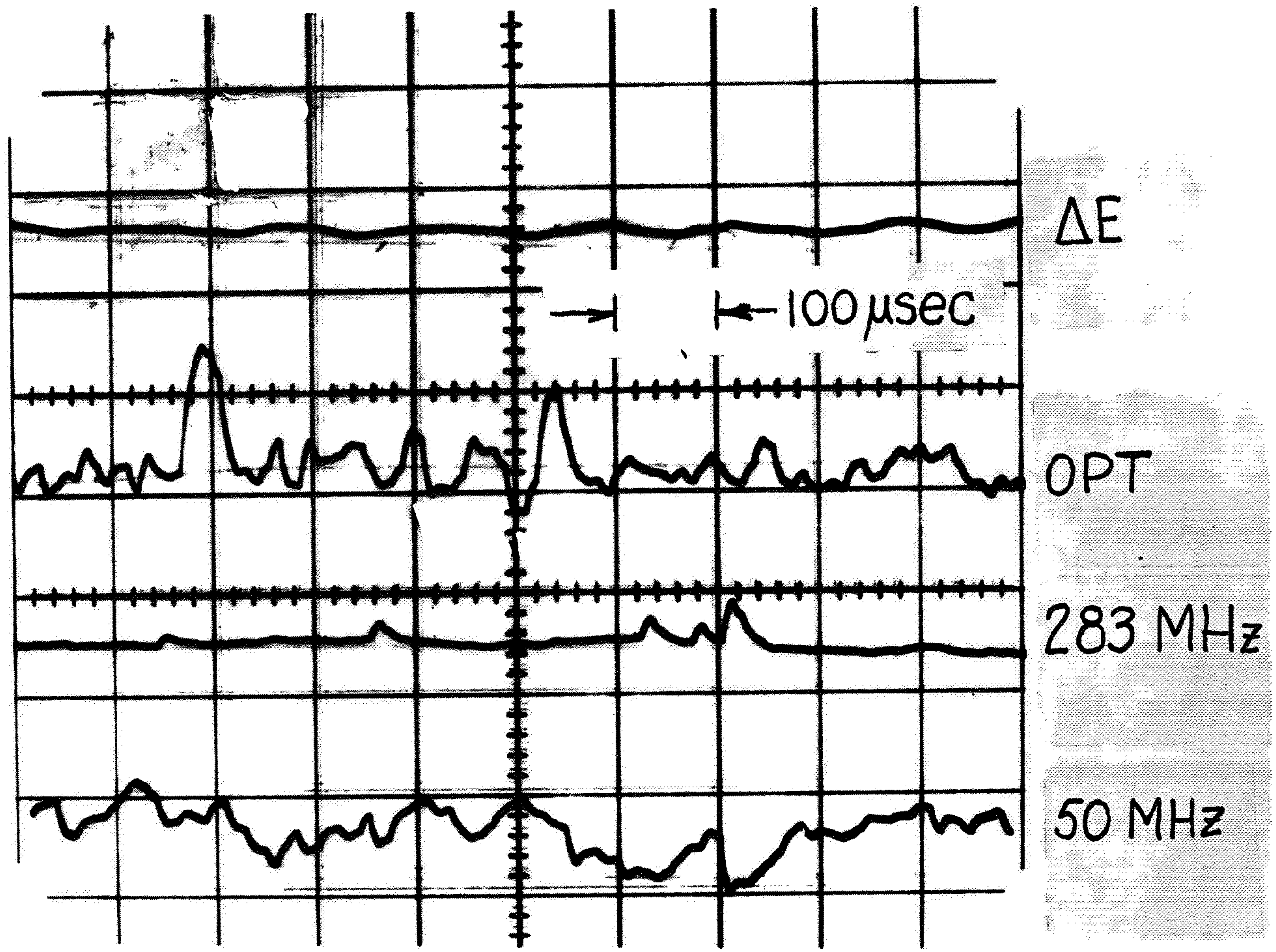


FIGURE 24. RADIO EMISSIONS ACCOMPANYING CLOUD FLASHES

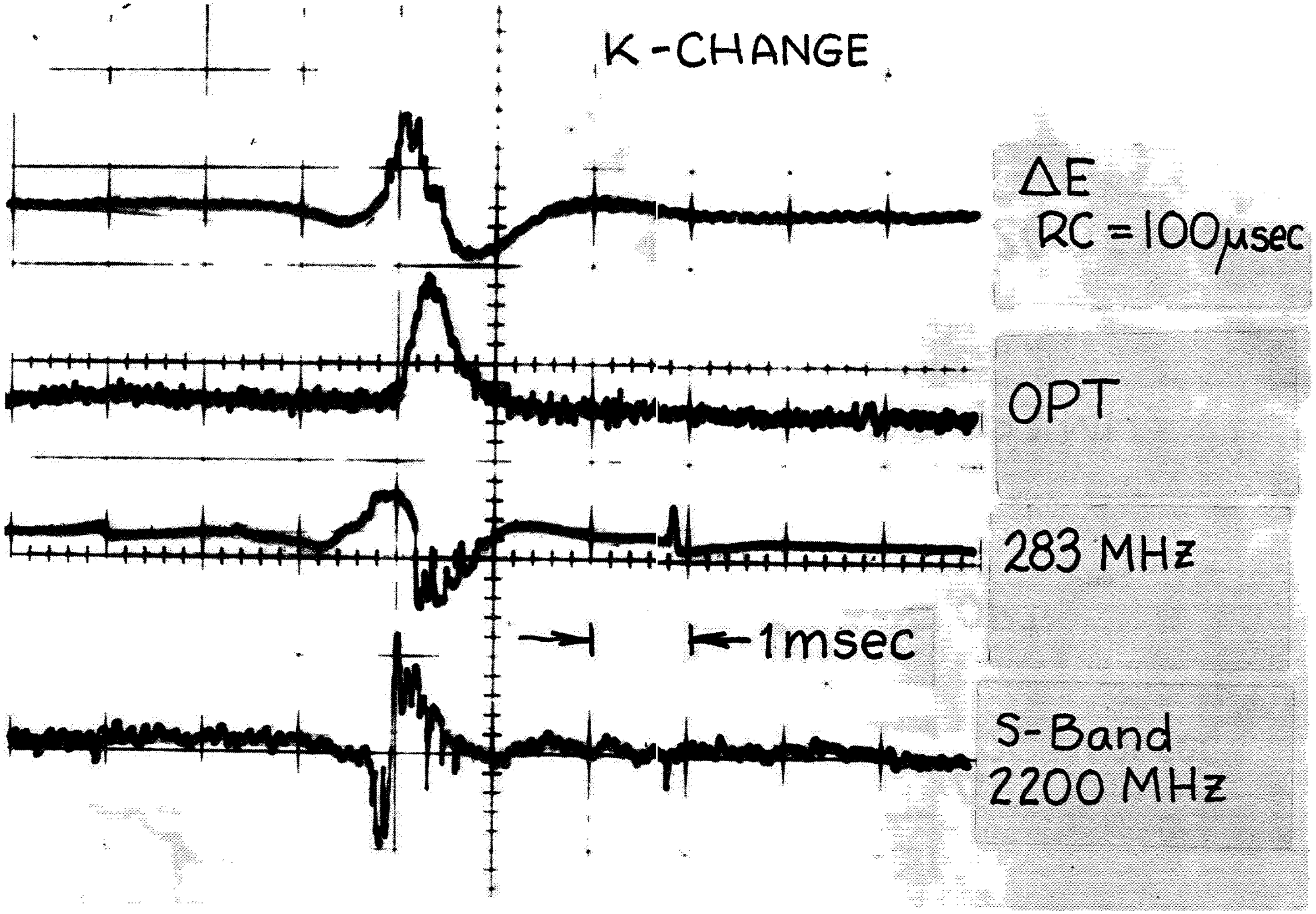


FIGURE 25 RADIO EMISSIONS ACCOMPANYING CLOUD FLASHES.

K-CHANGE

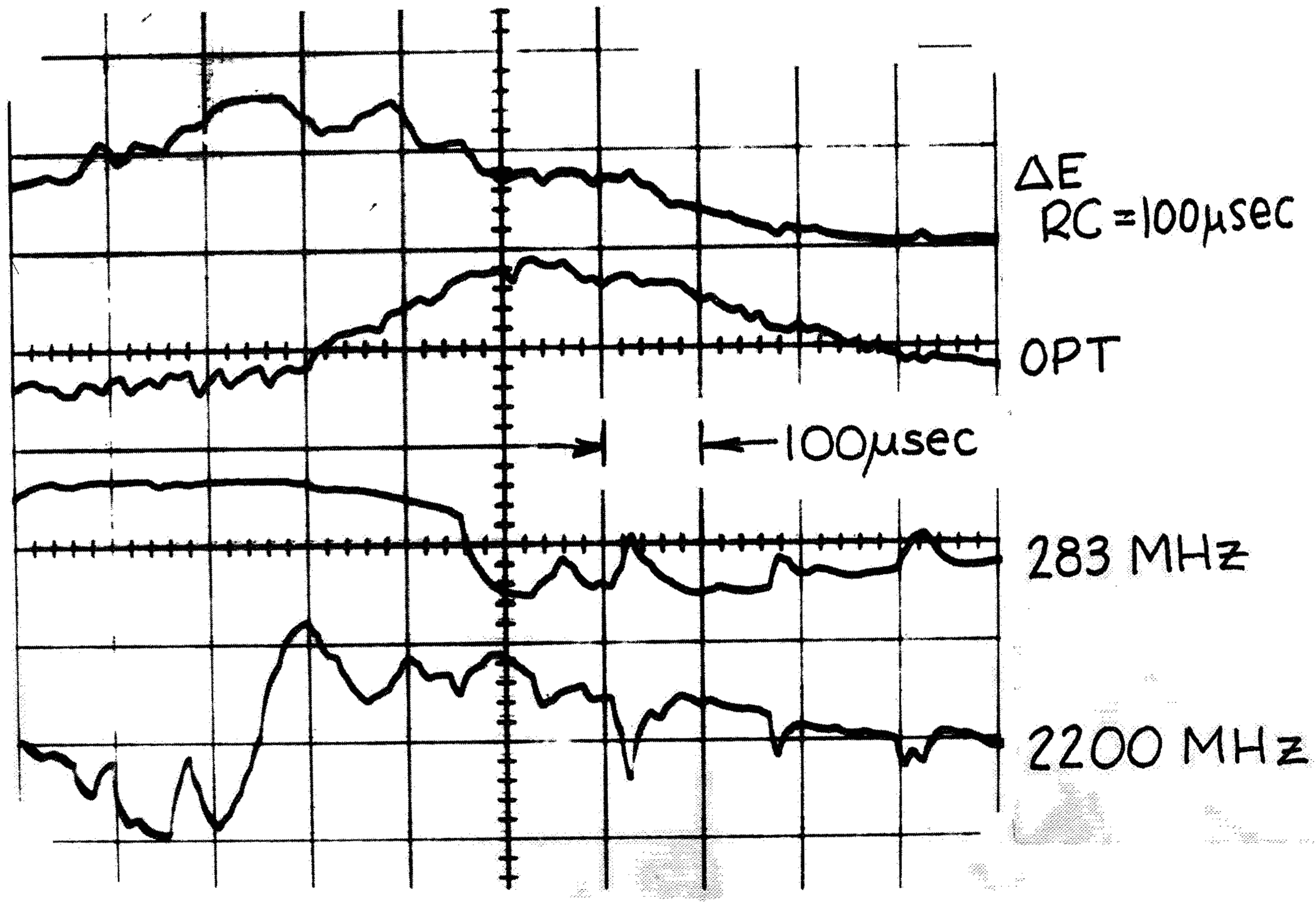


FIGURE 26 RADIO EMISSIONS ACCOMPANYING CLOUD FLASHES.

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A REVIEW OF SATELLITE LIGHTNING EXPERIMENTS

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Over the past five years a series of satellite optical experiments has been conducted to investigate terrestrial lightning. These experiments have been designed to gather statistical information about the optical waveform of lightning, measure occurrence rates, demonstrate the feasibility of detecting lightning from space platforms, and study possible applications for satellite lightning sensors. In this paper I will review these experiments, present some of the results, and discuss some ideas for future satellite systems.

SUMMARY OF EXPERIMENTS*

A. OSO. The first satellite-based lightning experiment was conducted as an adjunct to airglow measurements with optical sensors on Orbiting Solar Observatory (OSO) satellites (Vorpahl, et al, 1970; Sparrow and Ney, 1971). The high sensitivity of these instruments allowed detection of a large number of lightning flashes, but sunlight or moonlight reflections would saturate the system. Thus observations were limited to new moon, nighttime conditions. Even with this limitation, the University of Minnesota group was able to provide good nocturnal lightning distribution maps, based on 7,000 flashes from 1,000 storm complexes, concluding that the bulk of lightning activity was located over land.

B. VELA. The next set of lightning observations came from sensors which were originally thought to be too insensitive to ever detect lightning. These optical sensors were designed by Sandia Laboratories, Albuquerque, to detect atmospheric nuclear bursts, and were carried into orbit in the early seventies by four Vela V satellites. The Vela satellites are positioned in an inclined circular orbit with a geocentric radius of approximately 1.1×10^5 Km, providing essentially worldwide, full-time monitoring capability. Two wide field of view silicon photodiodes on each satellite provide time histories of rapidly changing optical signals near the earth, with an effective power threshold of about 10^{11} watts. A negative feedback circuit is used to cancel the slowly varying background signal due to sunlight reflected from the earth. When a rapidly increasing signal exceeds threshold, the photodiodes are triggered and collect a time history of the signal. The source of this signal is located with a segmented sensor, also using

*Portions of this paper are taken from an article "Remote Sensing of Lightning from Space," prepared for the American Scientist.

silicon photodiodes. Because of the longer integration time required by the locator, however, its effective threshold for lightning is about 3×10^{12} watts.

C. SSL. Even though the Vela threshold is much higher than the peak power radiated by most lightning flashes, we have detected considerable lightning activity with these sensors (Turman, 1977). But to investigate lightning phenomena in depth requires a higher sensitivity than Vela can give. How sensitive must a detector be? What is the statistical frequency distribution of peak power from lightning? This question was answered with data from an Aerospace Corporation experiment flown on DMSP Flight 33. This experiment was called the SSL (Special Sensor-Lightning). Although only a small amount of data were ever processed from this detector, a sufficient amount was gathered to give a good frequency distribution of peak power (Turman, 1978).

The SSL lightning detector consisted of 12 silicon photodiodes arranged so that each sensor saw a unique portion of the earth while the composite observed the complete field below the satellite (Figure la). The sensitivity range of the photodiodes was 10^8 - 2×10^{10} watts. No effort was made to cancel the reflected sunlight background, which was large enough to saturate the sensors. The detector was thus operational only during the dark (midnight local time) half of the sun-synchronous orbit.

D. PBE. Now armed with this information about the sensitivity range needed for detecting a larger fraction of the lightning activity, a new lightning experiment was designed by Sandia Laboratories. The PBE-2 (Piggyback Experiment) package was designed for integration into a small weight, volume, telemetry link, and power allotment available within the DMSP Block 5D, Flight 2 satellite. Because of these limitations, only a single photodiode, amplifier and digitizer channel could be used. The field of view of this photodiode was a cone of 40" half-angle pointed directly downward toward the earth, and covered an area on the ground of over a million square kilometers, somewhat larger than that of the two central photodiodes on SSL. Figure lb shows the single element field of view of the PBE-2. The primary purpose of the PBE-2 experiment was to gain more statistical information in the intermediate power range between the SSL and Vela sensitivity ranges (10^{10} - 10^{11} watts), to extend the SSL observation to daylight as well as darkness, and to gather worldwide lightning occurrence data. The sensitivity range of the PBE-2 is 4×10^9 - 10^{13} watts; and signal waveform sampling, digitized into 63 discrete logarithmically spaced intervals, is accomplished in much the same manner as for the Vela sensor.

E. SY/TY. The most ambitious lightning experiment to date is the SY/TY (this acronym doesn't really mean anything) launched in mid 1978 on Space Test Program vehicle S3-4. Again in a sun-synchronous orbit, this package views the earth at local times around 10 a.m. and 10 p.m. Primary objectives for this experiment are to gain higher location

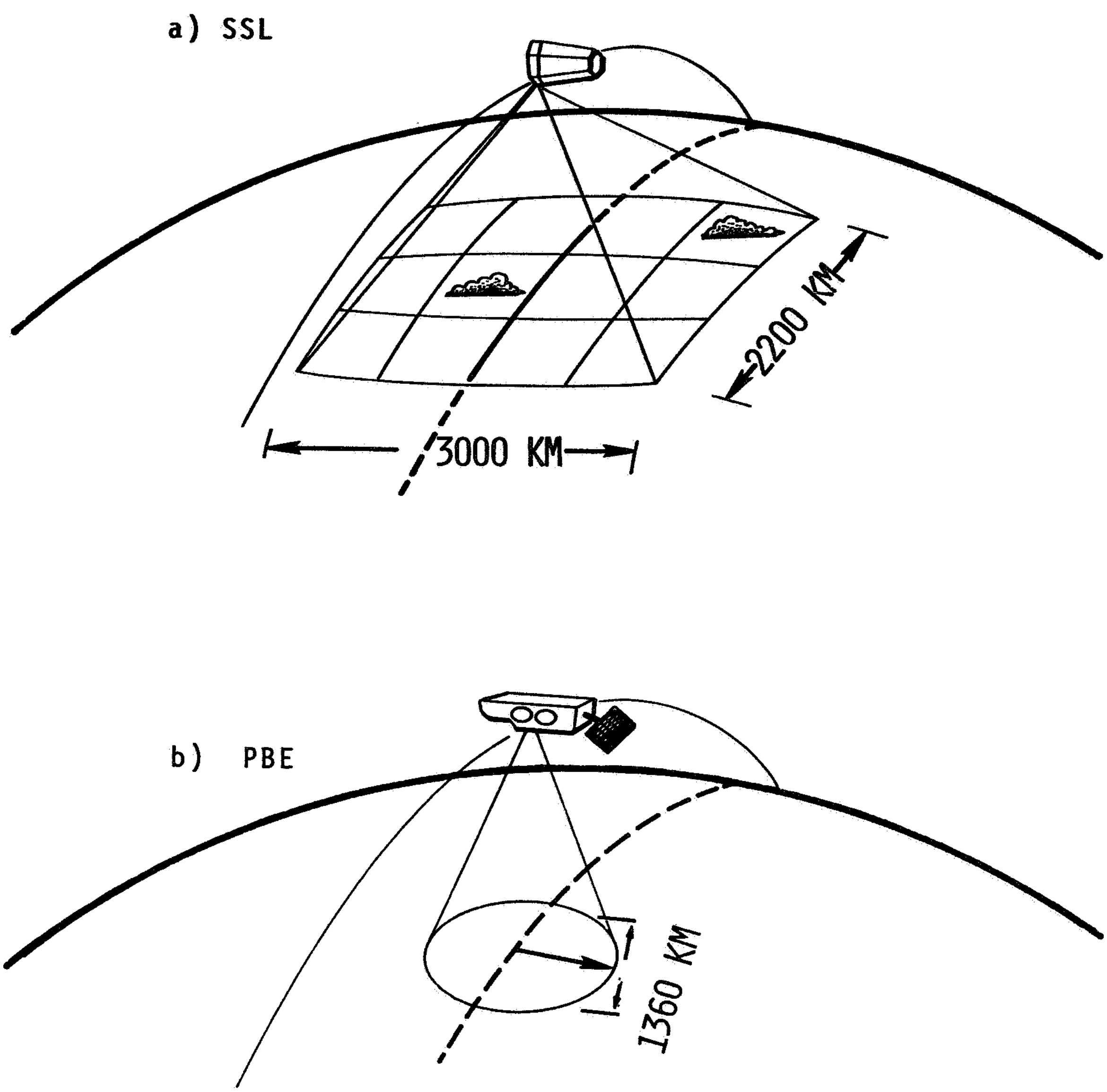

FIGURE 1. FIELD OF VIEW OF SSL AND PBE EXPERIMENTS ON DMSP SATELLITES.

resolution data and compare lightning activity at mid-morning/mid-evening with the dawn/dusk activity from PBE. A single-element, large field of view sensor similar to PBE-2 is included in SY/TY *for* the diurnal effect measurement. Two spatially resolved sensors, one scanning and the other a staring mosaic, give lightning locations with resolution on the order of kilometers. Analysis **of** these data has been delayed by ground-processing problems and few results are available as yet. Figure 2 summarizes the detection threshold and dynamic range of each of these experiments. Also shown in this figure is the expected cumulative frequency distribution for lightning flashes.

DATA REVIEW

A. Lightning Signal Characteristics. Analysis of data from these satellite experiments is being conducted primarily by Dr. Bruce Edgar (Aerospace Corporation) and myself and is proceeding along four basic avenues: lightning signal characteristics, lightning climatology, atmospheric electricity research applications, and severe storm detection. The SSL and PBE experiments on the Defense Meteorological Satellite Program (DMSP) satellites have given us statistics concerning signal characteristics of lightning. Some representative signal profiles from PBE are shown in Figure 3. The frequency of occurrence of peak optical power (wide-band silicon spectral range) is shown in Figure 4, taken from the SSL sensor (Turman, 1978). This curve can be approximated fairly accurately by a log-normal distribution with median of 1×10^9 watts and standard deviation of 10.8 decibels. The detector threshold for this experiment was 1×10^8 watts, so we do not know directly how many lightning flashes had power below this level. This figure can be estimated, however, by comparing Figure 4 with a similar set of data collected on the ground with a more sensitive instrument. This method indicates that about half of all lightning flashes are below the SSL threshold.

Pulse duration and rise time characteristics (Edgar and Turman, 1978) are shown in Figures 5 and 6. In these statistics, no effort was made to distinguish between first return strokes and subsequent strokes. Further analysis of the PBE data indicates that for the most part our sensor does not respond to subsequent strokes - subsequent strokes have been recorded for only about 10% of the flashes in our data base. This is probably to be expected, since ground measurements show that subsequent strokes are usually less intense than the first stroke (Norinder, et al, 1958). With more sensitive systems, we would expect to observe a larger fraction of multiple strokes.

B. Lightning Climatology. One of the primary goals of this project is to measure the geographical distribution of lightning activity. The relatively large field of view of the PBE sensor, however, allows only a coarse-grain development of this distribution. Figure 7 shows the geographical bins, 10° x 10°, used in sorting the lightning data. From its sun-synchronous, polar orbit, the DMSP satellite sees the

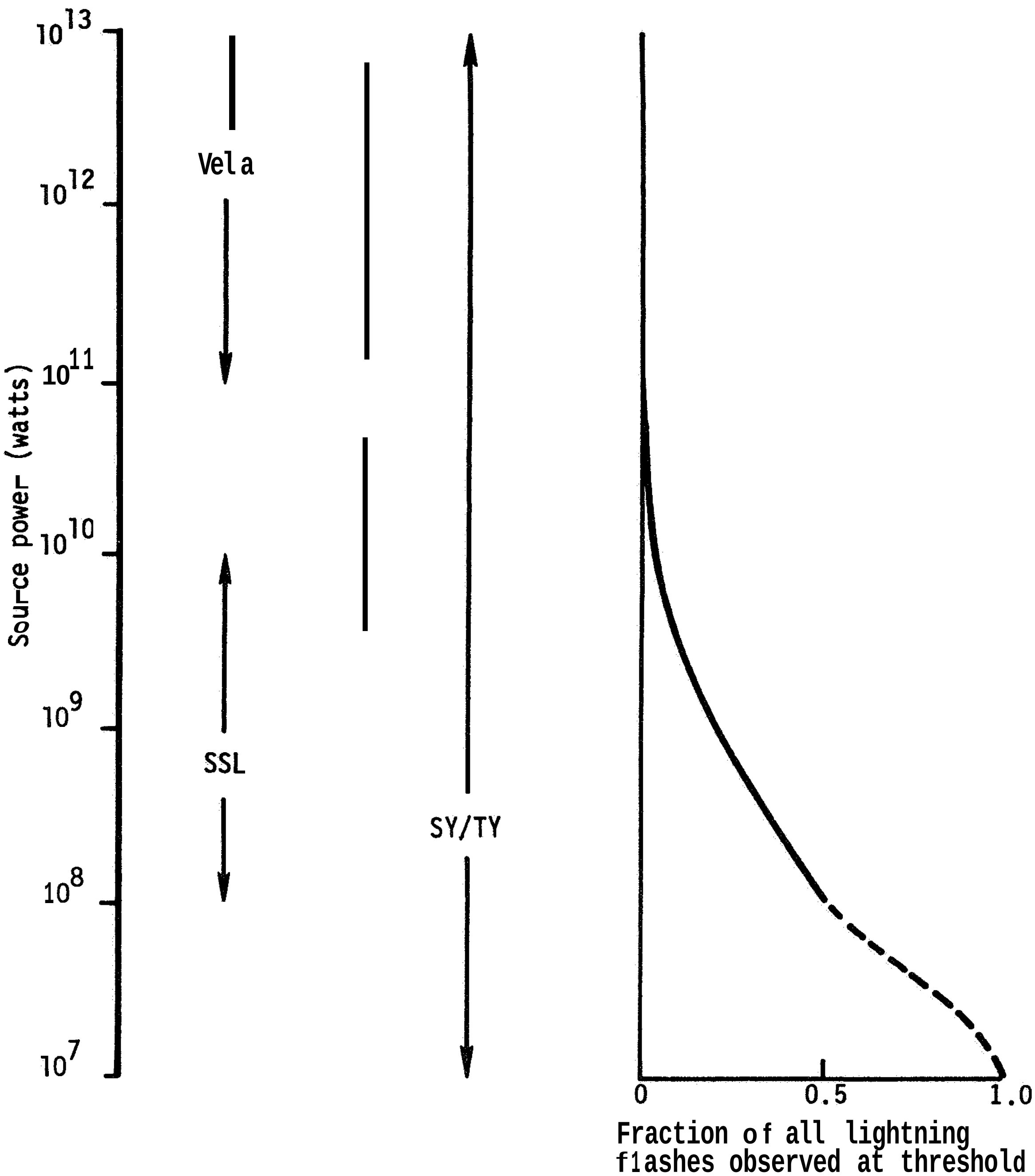

FIGURE 2. DETECTION THRESHOLDS FOR LIGHTNING EXPERIMENTS.

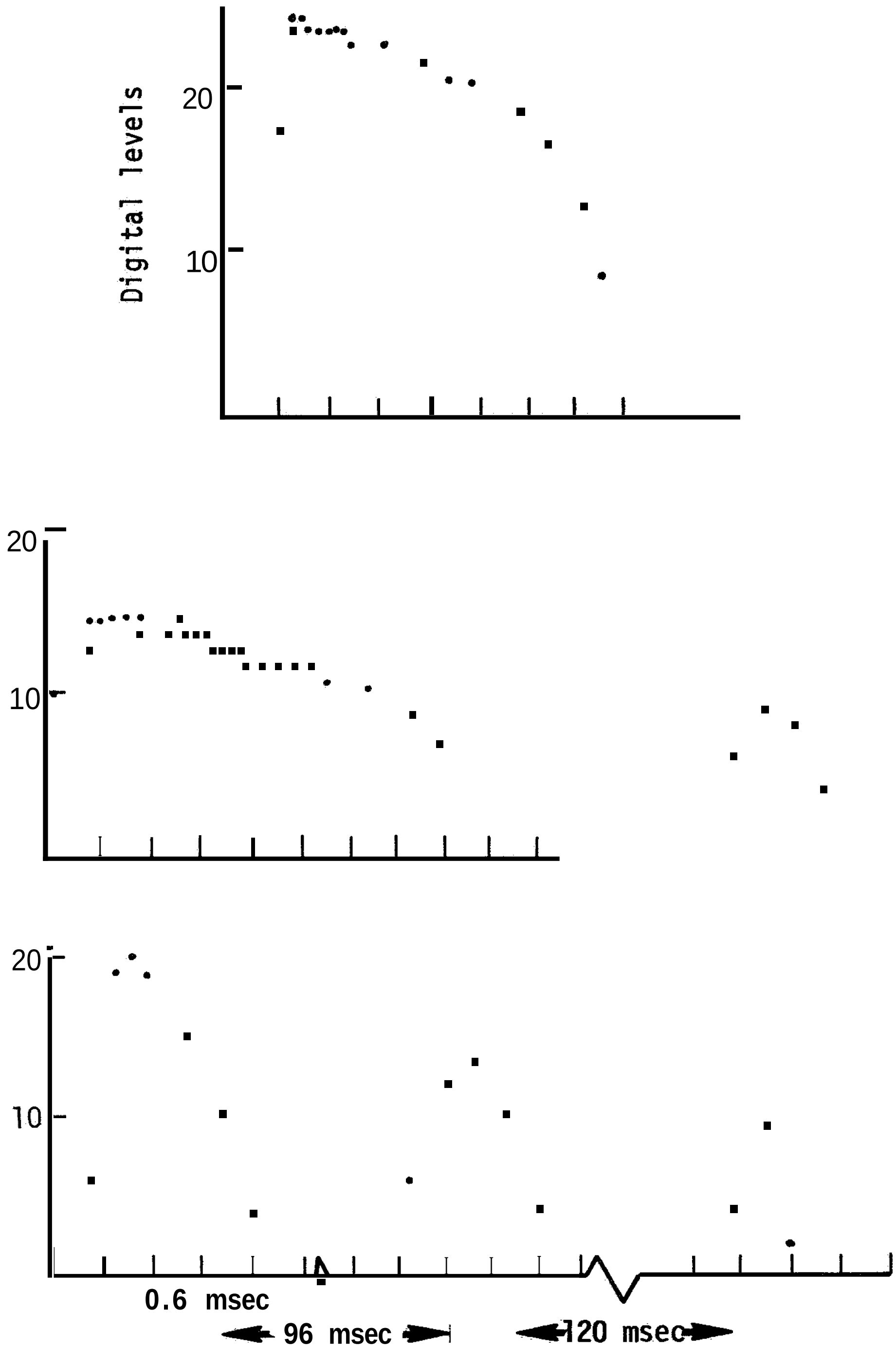

FIGURE 3. REPRESENTATIVE PBE LIGHTNING WAVEFORMS. TIMING RESOLUTION IS 32 MICROSECONDS; SOME DATA POINTS ARE OMITTED FOR CLARITY.

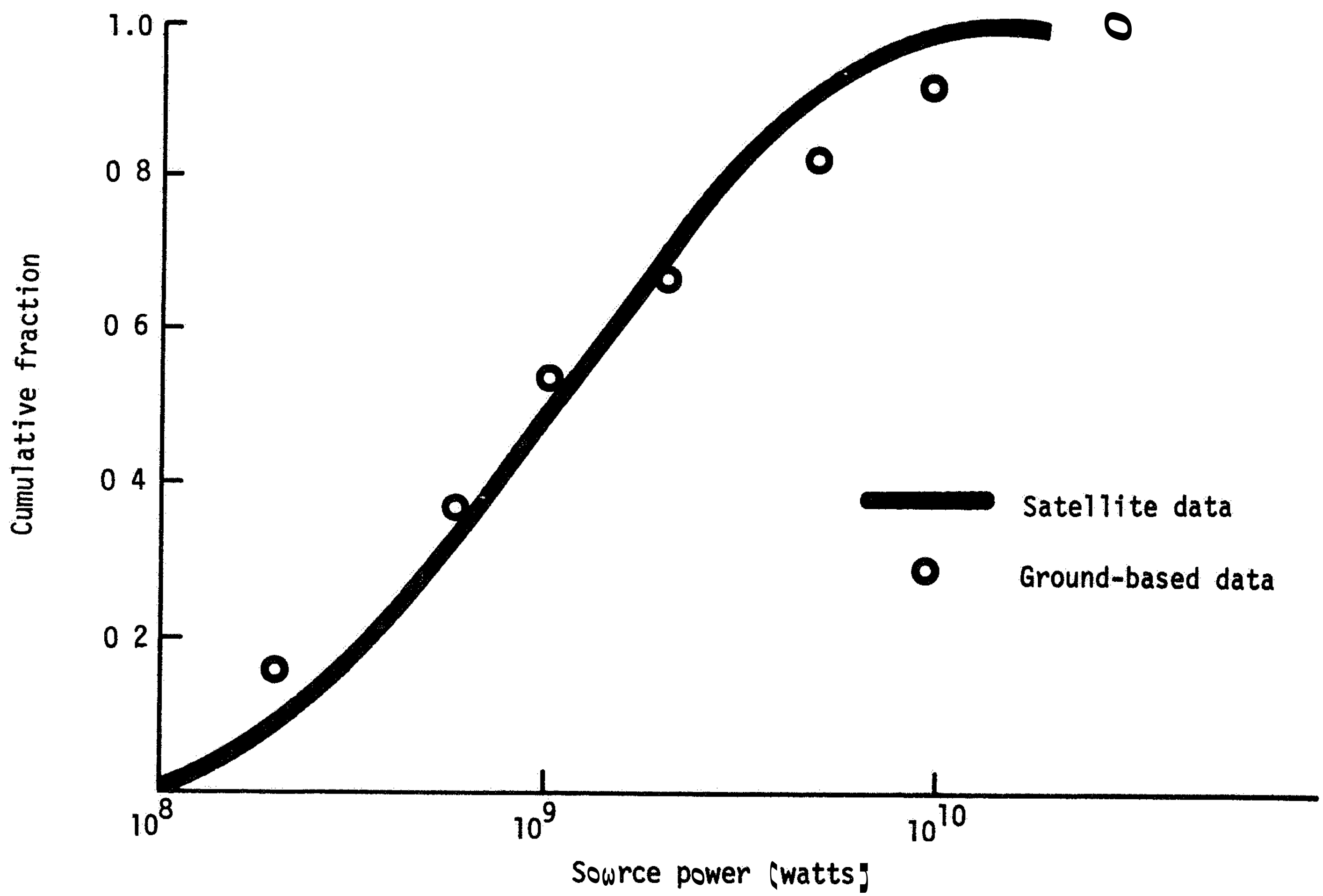

FIGURE 4. CUMULATIVE DISTRIBUTION OF PEAK OPTICAL POWER. SOLID CURVE IS SSL DATA. DATA POINTS ARE FROM GROUND-BASED EXPERIMENT.

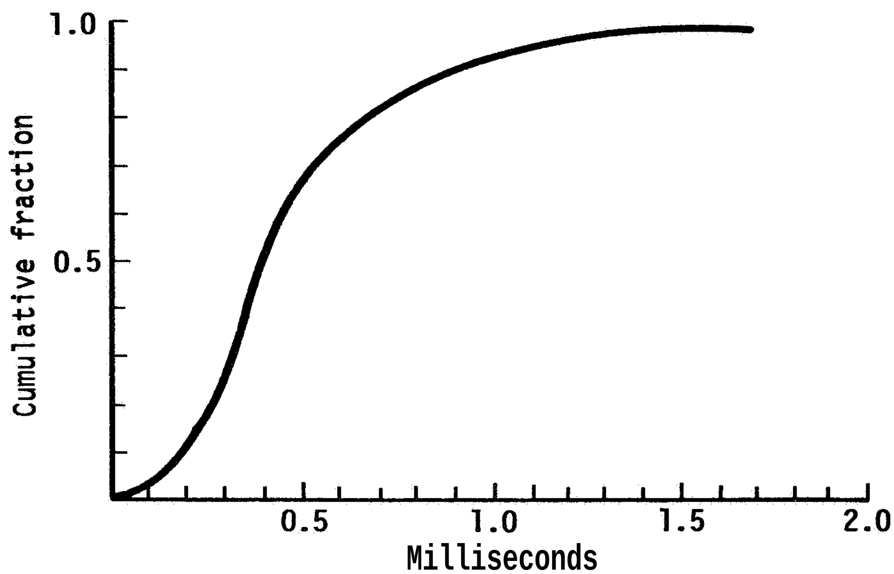

FIGURE 5. CUMULATIVE DISTRIBUTION OF PULSE DURATION.

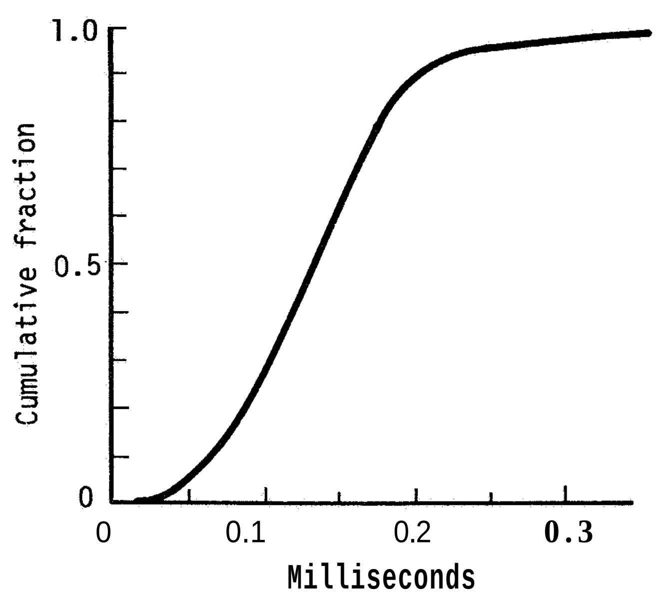

FIGURE 6. CUMULATIVE DISTRIBUTION OF SIGNAL RISE TIME.

DAWN

AUGUST 2-SEPTEMBER 10, 1977.

RATE (min^{-1})
0.2-0.5
0.5-1.0
1.0-2.0
2.0-4.0

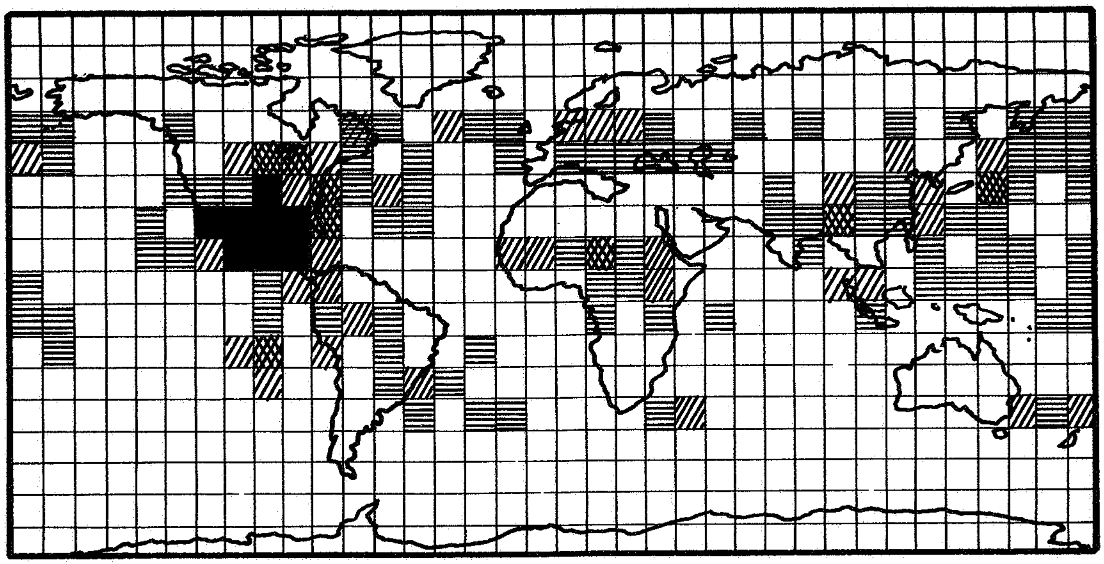

FIGURE 7a.

RATE (min^{-1})
0.2-0.5
0.5-1.0
1.0-2.0
2.0-4.0
> 4.0

DUSK

AUGUST 2-SEPTEMBER 10, 1977.

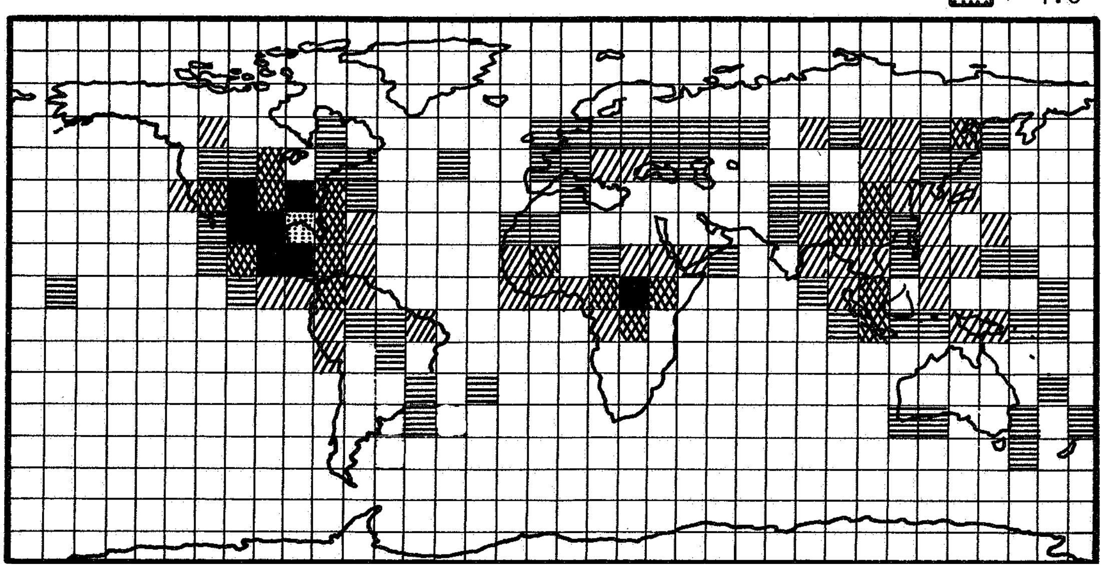

FIGURE 7b.

earth continuously at local times of dawn (approximately 0700) and dusk (approximately 1900). The orbital period is 100 minutes, and 15 orbits are completed each day. The result is that the satellite subpoint resides within each of these bins for an average of 1–5 minutes per day for each of the dawn and dusk passes.

Lightning count rate for each of the geographical regions was determined by counting the number of lightning strokes detected while the satellite subpoint was within that region and then dividing by the total time that the subpoint was within that region. Figure 7 shows the resulting distributions for dawn and dusk time frames for 2 August–10 September. Nominal sampling period for each of the 10" x 10" bins is 30 minutes. Table 1 summarizes the total lightning counts and integrated count rate for August–November. 1977.

TABLE 1

TOTAL LIGHTNING COUNTS

	Dawn		Dusk	
	Total	Per Minute	Total	Per Minute
Aug–Sep	2460	0.2	3013	0.3
Sep-Oct	3871	0.3	2900	0.2
Nov	2605	0.2	1269	0.1

The lightning data now available from the PBE experiment allows completely global, unbiased distributions of lightning activity which can be grouped by time (dawn/dusk) and month or season. The first of these distributions are shown in Figure 7; we are near completion of one full year of lightning distribution data. Some general trends can be deduced from these results. As would be expected, a definite diurnal trend is displayed over the land masses, with higher lightning activity at dusk as opposed to dawn. The reverse trend is noted over the oceans, with higher activity at dawn. Ocean activity is considerably lower than that over land, but there are a few pockets of significant lightning activity (0.5 - 1.0 per minute, level 2) over the oceans. During the Aug-Sep time frame, one such area is off the west coast of South America, centered at 10°S, 100°W, and another is in the South Pacific off the east coast of Australia, around 30°S, 170°E. The North Atlantic also has some regions with level 2 lightning activity.

The regions of highest lightning activity are easily identified in the distributions, and correspond well with those areas classically regarded as lightning capitals of the world. The August-September distributions show the following high activity areas: (a) Southeast United States, Gulf of Mexico, and Central America (bounded roughly by latitude 10° - 40°N, longitude 80° - 110°W), (b) Central Africa (Zaire and the Congo basin), (c) Southeast Asia (Malaysia, Sumatra, Borneo), (d) India and Southern China. Note that there is little diurnal variation for the southeast United States, Gulf of Mexico region, probably because the warm Gulf waters can maintain through the night thunderstorm activity initiated over land regions during the day.

Definite seasonal changes are seen in our data as we progress toward Northern Hemisphere winter (these figures are not included here for brevity, but will be shown at the meeting). In these winter months, the majority of lightning activity is in the Southern Hemisphere, particularly concentrated over central South America, South Africa, and Indonesia.

C. Atmospheric Electricity Research Applications. The applications of these satellite data to atmospheric electricity research are legion, and we have only begun consideration of the possibilities. One of our most important initial investigations in this area is a ground-truth experiment to correlate ground observations with satellite data. Such correlation was first attempted during the Thunderstorm Research International Program - 1977 (TRIP-77) with ground based rf sferics locating equipment operated by Dr. Uman's group from the University of Florida (Beasley, et al, 1978). Coincidences between the satellite and ground systems were recorded for many storms, but the poor resolution time (4 seconds) of our first PBE sensor (PBE-2) has hampered the analysis. A second attempt at this correlation was conducted during TRIP-78, this time with a much improved timing accuracy (± 1 millisecond error) from our new PBE-3 sensor now on orbit. Analysis of these new results is now underway. Thus far, this ground-truth test has given renewed confidence that the satellite is detecting lightning and also shows that cloud-ground discharges (the type detected by the sferics system) as well as cloud-cloud lightning can be seen from the satellite. There is also at least a glimmer of hope that we can discriminate between cloud-cloud and cloud-ground discharges on the basis of the optical waveform.

Diurnal variation of lightning activity is an important area of interest, but unfortunately the orbit of the PBE experiment gives information only at dawn-dusk (0600-0800/1800-2000 local time). Some additional information from mid-morning/mid-evening times (1000 and 2200 local times) will be available from SY/TY. The Vela satellites do give us an opportunity to see lightning activity at all time periods, but of course only the large flashes above 10^{11} watts are observed. Figure 8 shows a histogram derived from about 5,000 Vela lightning signals. This curve shows a bimodal distribution, with peaks at about 0400 and 1800 local time. The 1800 peak is what we would expect from land mass activity, and the 0400 peak is also to be expected from ocean thunderstorms. However, I would not expect both peaks to be of equal intensity as shown in the data. This may be peculiar to the large power "superbolts," which seem to prefer water.

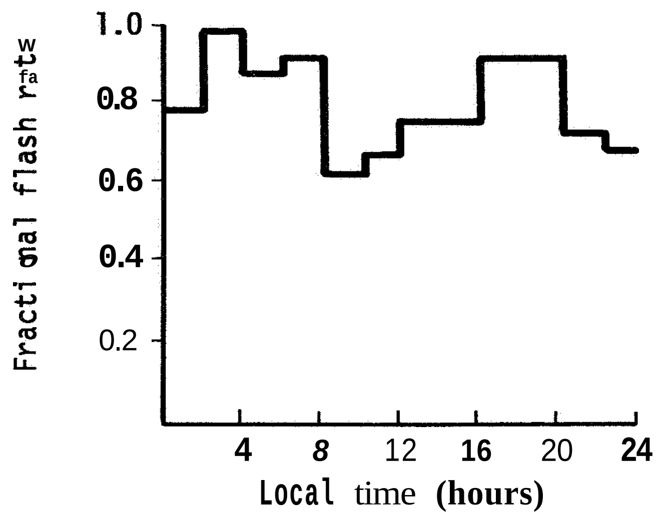

FIGURE 8. DIURNAL VARIATION OF VELA LIGHTNING ACTIVITY.

It seems that almost everyone these days is looking for correlation between solar activity and weather variations on the earth. When an appropriate lightning data base is obtained, I think that solar-lightning activity correlations will be an important stepping stone in clarifying our knowledge of solar effects on weather. Our PBE data base is not well suited for this application right now, primarily because of limited field of view and significant periods of missing data (because of data processing priority conflicts). We are hopeful that almost continuous data processing support for PBE has (or will) become a reality, and we continue to look into this application. In the meantime, the Vela system provides an opportunity to explore the possibilities of correlating lightning and solar activity. The Vela data base has the advantage of worldwide, full-time coverage, but is severely limited by the high threshold. Figure 9 shows an epoch analysis of Vela lightning activity, where the key day (day zero) is the solar sector boundary crossing. This curve does show structure which is similar to that reported by Wilcox (1976), Markson (1971), and Park (1976). In Figure 10, the key day is the occurrence of a solar flare. Again, this curve displays some similarities with epoch analyses of other terrestrial phenomena (Wilcox, Markson, Park). In both of these Vela data displays, however, there are not enough samples to draw any good conclusions. More sensitive systems, with worldwide coverage, are needed.

D. Severe Storm Detection. The final area of lightning data analysis that I will discuss is that of severe storm detection. We have seen lightning from hurricanes, and in fact it appears that a substantial fraction of the oceanic lightning activity is hurricane-related. We are also studying the relation between tornado activity and lightning trigger rates over the central United States, with the cooperation of Dr. Rust of the National Severe Storms Laboratory. In Table 2 I have some preliminary results which look encouraging. This table shows the number of triggers and peak intensity of lightning signals collected at dusk over the Central United States during April, 1978. In most cases, it appears that the number of triggers, and to a lesser extent the peak intensity, is an indication of severe storms. One notable exception is the tornado reported on 8 April. Further work is required to tell whether this will be an accurate, effective means of labelling severe storm activity.

WHAT NEXT?

Data continues to pile in on us from the PBE (and maybe SY/TY) experiment. As I indicated in the previous section, we are analyzing these data from several perspectives simultaneously and have not yet reached the full potential of the experiment in any of the areas; but eventually we will, because the sensor itself has limitations. What should be done in the area of satellite lightning detection beyond our present experiments? I see three major projects, and probably more will crop up as we progress. These follow-on projects are: (1) low altitude lightning survey satellites, (2) severe storms correlation

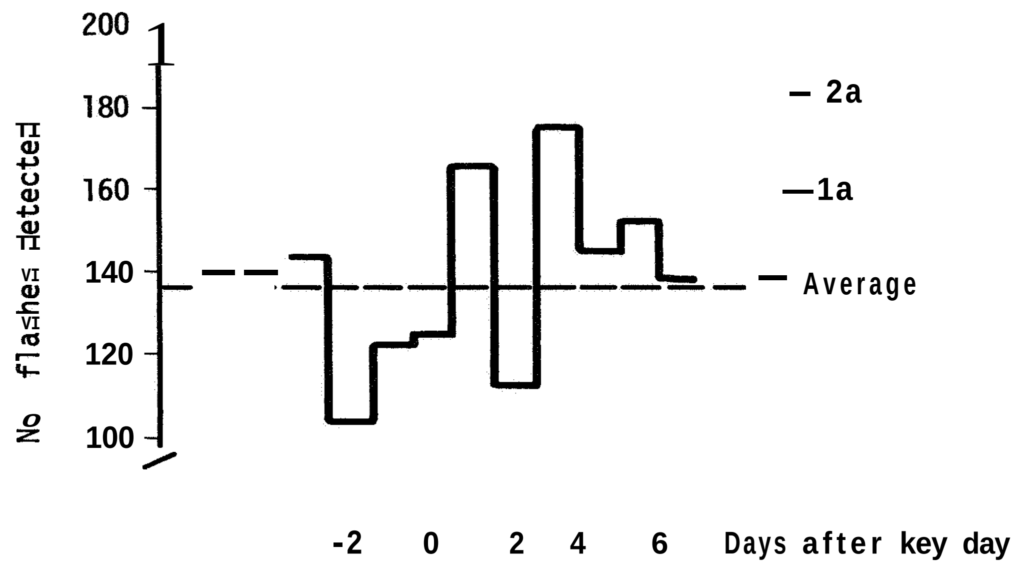

FIGURE 9. EPOCH ANALYSIS OF VELA LIGHTNING ACTIVITY.
KEY DAY IS SOLAR SECTOR BOUNDARY CROSSING.

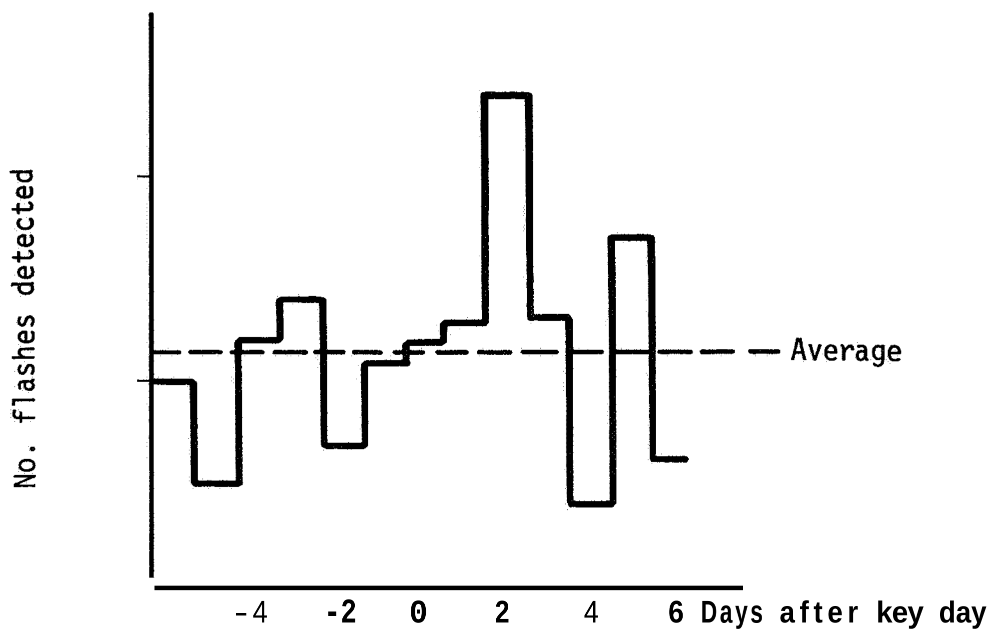

FIGURE 10. EPOCH ANALYSIS OF VELA LIGHTNING ACTIVITY.
KEY DAY IS SOLAR FLARE OCCURRENCE (BASED ON 11 FLARES).

TABLE 2

CENTRAL U.S. SATELLITE OBSERVATIONS (APRIL)
DUSK

DATE(CST)	WEATHER REMARKS*	NUMBER TRIGGERS (0 10 20 30 40)	PEAK INTENSITY (0 10 20 30)
5	HEAVY RAIN		
6			
7	TORNADO	NO DATA	
8	TORNADO		
9			
10			
11			
12			
13		NO DATA	
14		NO DATA	
15			
16			
17	TORNADO OUTBREAK		
18	TORNADOES		
19			
20			
21			
22	7 TORNADOES		
23			
24	FLOODS		
25			
26		NO DATA	
27		NO DATA	
28		NO DATA	
29			
30	TORNADOES, T.STORMS		

*INFORMATION TAKEN FROM WEATHERWISE, JUNE, 1978.

experiments, and (3) development of a lightning activity locator with prototype testing at synchronous altitude.

A. Low Altitude Lightning Survey Satellite. Figure 7 suggests the potential to be offered by satellite lightning survey instruments, but the present sensitivity and location resolution of PBE are probably inadequate for the majority of present applications. This situation can be remedied with a rather modest advance in sensor design. For a ballpark system analysis, let us consider a resolution of 1° latitude/longitude on earth. This is ten times the resolution of PBE and would require that we either: (a) scan the present PBE sensor, (b) use 100 of the present PBE detectors, or (c) use a 10 x 10 photodiode matrix. All of these alternatives are well within present technology. Since the principal limitation to the PBE sensitivity is background illumination, narrowing the field of view of the detector allows us to make the sensor more sensitive. Thus a factor of ten increase in sensitivity, with an attendant increase of a factor of ten in the lightning detection rate, should be easily attained. The traditional weather satellite altitude of 800-1500 Km should be a good place to put the sensor. A great cost saving could be realized if the survey instrument could be designed into another satellite system as an additional package (the piggyback concept). For this survey, the optimum orbit would have an inclination of somwhere around 60°, allowing one to survey the major lightning production areas of the earth on a thorough basis and also covering the full diurnal cycle.

The primary goals for this survey experiment would be to (a) generate higher resolution lightning climatology for lightning hazard and industrial siting surveys, (b) provide the basis for additional ground-truth experiments, and (c) provide a much improved data base for solar-terrestrial correlations and other lightning-related research studies. A bare minimum of two satellite packages should be flown, and up to six would be productive. It would also be beneficial to fly the packages in pairs, to serve as a cross-check on the systems and also look for lightning activity asymmetries.

B. Severe Storms Correlation Experiment. Monitoring and tracking severe storms is a promising application of the satellite data, but more information is needed to establish firm correlations between storm severity and lightning output. Some of these data could be derived from the lightning survey experiment, but a good understanding of the lightning phenomena in severe storms will require very high lightning location resolution, detailed cloud structure information, and probably lightning spectroscopic information as well. Thus it seems that this experiment would require a high resolution lightning "telescope," a lightning spectrometer, and cloud photography capability. The space shuttle experiment being planned by Vaughan and Vonnegut is a good start in this direction.

C. Synchronous Altitude Locator. If lightning signals can be used to identify severe storms, then a prototype lightning locator should be flown to test the feasibility and usefulness of a severe storms alerting system. The most practical position for such a locator is above the United States at geosynchronous altitude (about 34,000 KM). In fact, the GOES satellites are already there - so an immediate thought is to piggyback the prototype onto GOES. But even better from the sensor design point of view would be NASA's proposed Stormsat, a three axis stabilized satellite, which would also be synchronous.

I have done a conceptual design study of such a locator (Turman, 1978b); the basic detector concept uses two linear photodiode arrays as shown in Figure 11. The major difficulty seems to be in trading off detector sensitivity, location accuracy, and sampling frequency. I will not go into detail here, but just summarize the design results. Table 3 gives the expected lightning flash detection rate from a single severe storm and the collection time required to identify the storm as severe (based on its lightning flash rate). These values are shown parametric in the sensor power threshold P_{thres}. Table 4 show detector design parameters S (location resolution), N (number of elements in photodiode array), and the sampling frequency. To effectively identify severe storms and provide any warning, it seems that a detector threshold of 2 - 10 x 10^9 watts source power, between 200 and 1,000 element arrays, and sampling frequency around 1 MHz would be required. The component design of this system would be no mean task, but does seem to be within the realm of present technology.

TABLE 3

FLASH DETECTION RATES FOR A SINGLE SEVERE STORM*

P_{thres} (watts)	Flash Detection Rate (min^{-1})	Collection Time** (50% error)	Mn (20% error)
1 x 10^9	4.4	1	5
2 x 10^9	4.0	1	5
5 x 10^9	1.0	4	20
1 x 10^{10}	0.2	20	100

*Flash rate of the storm is assumed to be 20 min^{-1}.
**Time required to establish flash rate to the prescribed accuracy.

a

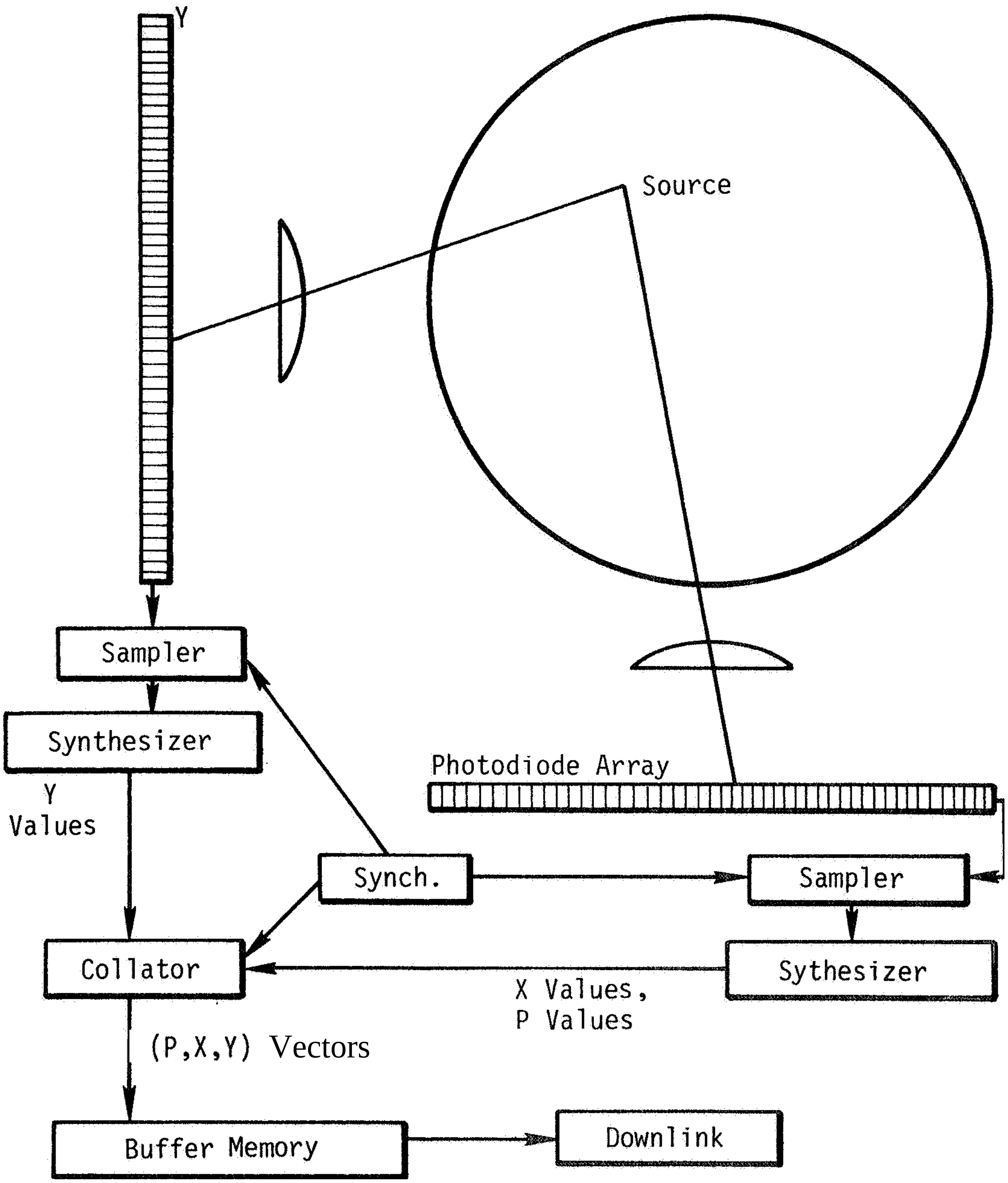

FIGURE 11. PHOTODIODE ARRAY LOCATOR CONCEPT.

TABLE 4

DETECTOR DESIGN PARAMETERS

P_{thres} (watts)	S Km	N	Sampling Frequency MHz
2×10^9	4	1,000	1.00
5×10^9	9	450	0.45
1×10^{10}	18	220	0.22

CONCLUSION

The data from the current satellite experiments have shown that lightning can in fact be detected by satellites, that satellite lightning detectors can be operated reliably in sunlight as well as at night, and that lightning climatology can be easily developed from space platforms; the data also suggest that severe storms may be identified from their lightning activity. These experiments do not represent the best we can do in this field--they are but the beginning.

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STATE OF TECHNOLOGY IN OPTICAL SYSTEMS

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The Aerospace Corporation

SILICON PHOTODIODE SENSORS

Over the past few years silicon photodiode sensor technology has reached a level of sophistication that has enabled three lightning detection systems to be flown on the DMSP satellite series. These lightning experiments were stimulated in part by the detection of very powerful lightning "superbolts" on the high altitude Vela satellites (Turman, 1977). The characteristics of each of these systems are described in Table 1. The state of the technology is described by the lightning source power sensitivity range. Turman, et al. (1976) established from ground optical measurements of lightning that the average source power is probably between 10^8 and 10^9 watts. Thus the lowering of the power threshold from 10^{11} (Vela) to 10^9 (PBE) and 10^8 (SSL) allows a better sampling of lightning activity.

The main limitation to the detection of lightning flashes from satellite altitude is the earth's albedo which can be on the order of 10^8 watts/km2 from a fully illuminated earth. The SSL sensor was only operated at local midnight so that there were no background problems. However the PBE series flew on a DMSP dawn/dusk satellite and could encounter a total background power of 10^{16} watts in its field of view and 10^{11} watts from cloud sun glints. Thus the detection of flashes of 10^9 watts in the midst of this environment is not an easy task. However the background is nearly constant for the most part and can be subtracted out, leaving only time varying optical phenomena (e.g., lightning flashes). The 10^9 watts threshold of the PBE series can be improved upon by increasing the size of the sensor to 1" diameter to give a 10[illegible] watts threshold. An experiment incorporating a 1" sensor has been proposed for the NASA Upper Atmosphere Research Satellite (UARS) by Sandia Laboratories and Aerospace Corporation (Edgar et al., 1978).

The silicon photodiode sensors allow the power-time profile to be measured from satellite altitude. From ground-truth experiments performed in Florida during TRIP-77 (Edgar et al., 1979), we have determined that the power-time profile of negative ground return strokes can be easily differentiated from those of intracloud and positive flashes. The differences between the latter two categories' optical signatures will be the objective of ground-truth experiments to be performed in summer of 1979. Hopefully, the correlation of the DMSP lightning data with severe weather observations will allow the unique determination of lightning optical signatures associated with such phenomena.

TABLE 1

OPTICAL LIGHTNING EXPERIMENTS

(Silicon Detectors)

Satellite	Lightning Power Sensitivity (watts)	Sensor	Locator
[1]Vela (Turman, 1977)	$10^{11} - 10^{13}$	photodiode	Gray code ($> 10^{12}$ watts)
[2]DMSP-SSL (Turman, 1978)	$10^{8} - 10^{10}$	12 photodiode array	4 x 3 array
[1]DMSP-PBE-2, -3 (Edgar et al., 1979)	$10^{9} - 10^{13}$	0.1" photodiode	-----
[1]UARS (proposed) (Edgar et al., 1978)	$10^{8} - 10^{13}$	1" photodiode	Grey-code ($10^{8} - 10^{13}$)

[1]Built by Sandia Laboratories

[2]Built by Aerospace Corporation

LOCATOR SYSTEMS

An equally important requirement for a lightning detection system is a good locator. The main problem with locator systems is that it is difficult to arrive at the same sensitivity threshold as the silicon photodiode sensor. The Vela locator system only operated above 10^{12} watts. The SSL sensor used a 4 x 3 array to give a gross position. (The PBE series had severe weight and power restrictions which precluded a locator system.) The proposed UARS system will use a grey code locator system similar to that which was used by Vela.

An example of a grey code locator system for a low altitude satellite is shown in Figure 1. One axis is shown. Location is accomplished by the utilization of a two-axis or a three-axis system. Each locator axis employs a cylindrical lens to focus point sources on the earth to a line across an 8-element grey code masked photodiode array positioned in the lens image plane. The unmasked chip is used as a reference line, and the remaining seven are masked in such a way that the on/off status of each line (compared to the reference line) produces a 7-bit number indicating position of the focused line on the sensor. A better than 10 km resolution at 500 km is possible with the system. The grey code sensor is AC coupled, reducing any serious background problems. When the main photodiode sensor detects a lightning event, the locator system is sampled at approximately the signal peak to give a position. Thus in response to a lightning flash detected by the satellite, a power-time profile is measured and a position is computed. The data rate associated with such a measurement is relatively modest and only depends upon the flash rate encountered.

Another device to do location measurements is the Reticon photodiode linear array. The array detects lightning flashes by taking the difference between the charge reading on one element and the reading on the previous sample. In order to overcome the background, the array must be sampled at a high frequency. The sampling changes the DC character of the information from the array to the small perturbations of light intensity due to lightning flashes. A locator system using the arrays for a synchronous severe weather satellite has been proposed by Turman (1978). We will use his basic parameters to show the requirements for a low altitude locator system similar to the previously discussed grey code system. This is described by Table 2.

For a 10 km resolution along a 1000 km strip, we would require an array size of 100 elements. The dynamic range is determined by the background charge C_B and the dark current corresponding to the threshold charge C_{THRES}. In our example it is $\sim 10^3$. The power threshold is 10^9 watts, and the sampling rate is 100 kHz. If we want 10^8 watts threshold, this requires a 1000 element array and a sampling frequency of 1 mHz.

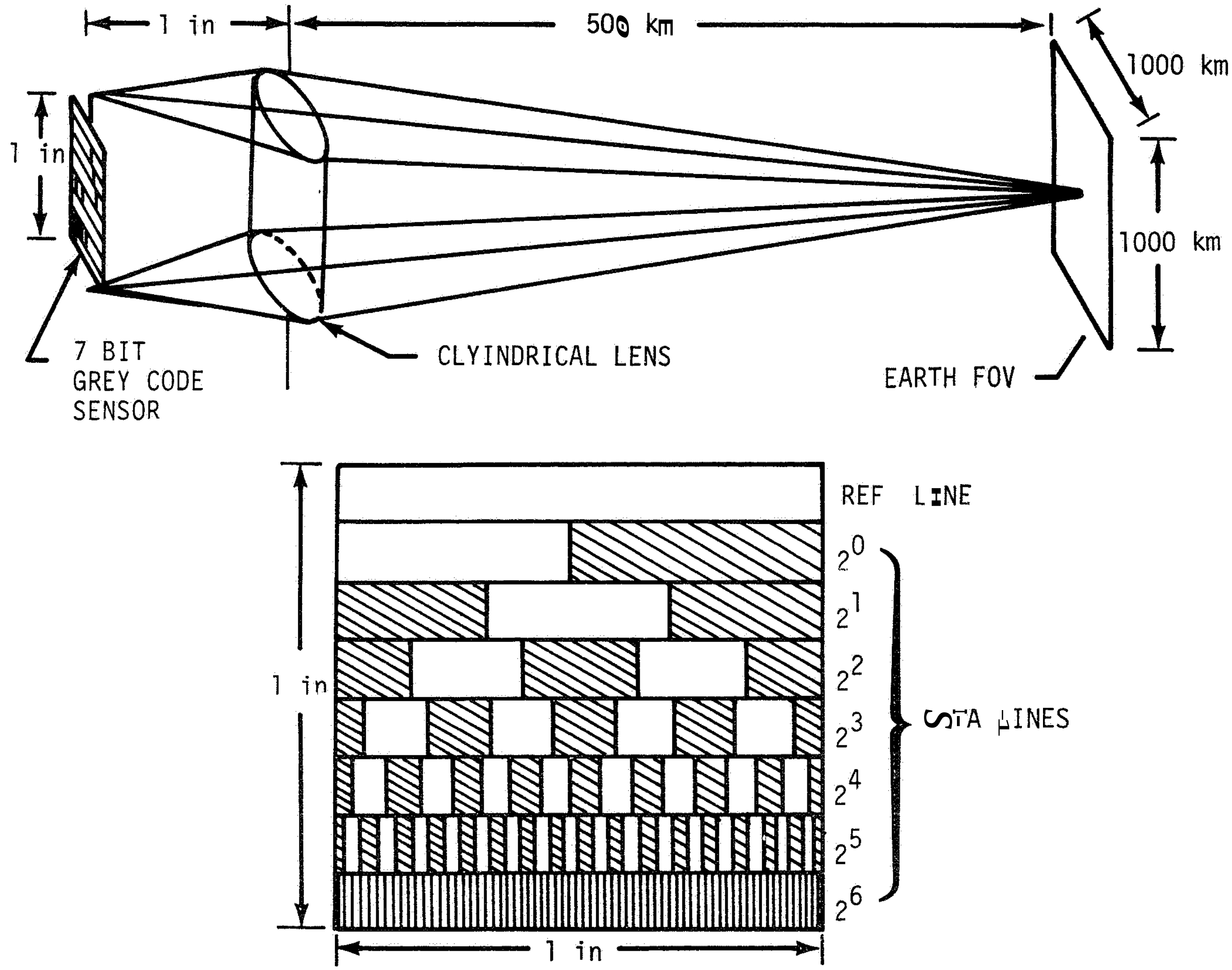
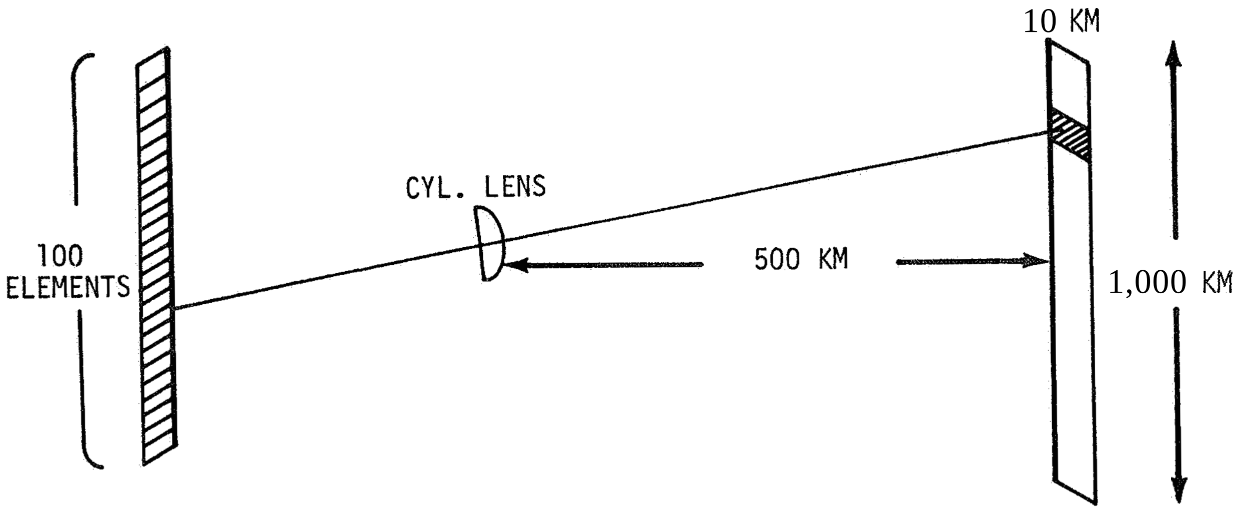


FIGURE 1. GREY CODE LOCATOR SYSTEM FOR A LOW ALTITUDE SATELLITE

TABLE 2

RETICON PHOTODIODE LINEAR ARRAYS

Example: 10 km resolution @ 500 km.



for collection time of 1 msec.

$C_{BACKGROUND} = 2.2 \times 10^{-12}$ coul. (saturation)

$C_{THRES} = 3 \times 10^{-15}$ coul. (dark current)

$P_{BACKGND} = 10^{8}\left(\frac{WATTS}{km^2}\right) \cdot 1000 \text{ km} \cdot 10 \text{ km} = 10^{12}$ watts

$P_{THRES} = P_B \cdot \frac{C_{THRES}}{C_B} \cong 10^{9}$ WATTS

Sampling Freq = 10^3 (# ele) = 10^5 = 100 kHz

For 1 km Resolution (1000 ele)

$P_{BACKGROUND} = 10^{8} \cdot 1000 \cdot 1 = 10^{11}$ WATTS

$P_{THRESHOLD} \cong 10^{8}$ watts

Sampling Freq = 1 mHz

Table 3 gives an outline which compares the basic features of the grey code versus the Reticon arrays. Essentially the two devices accomplish the task of location with good resolution and sensitivity. The big difference is the data rate required. For the situation of a low altitude, low power-telemetry lightning survey satellite, the grey code device would be the best choice. For large systems using high data rates the Reticon would compete on an equal basis with the grey code for a locator system.

TABLE 3

LOCATOR SYSTEMS

GREY CODE	RETICON
1. Locates lightning signal by on/off comparison of multi-segment strips to reference strips.	1. Locates lightning signal by comparison of sweeps to one another and detecting differences.
2. AC Coupling - no severe background problem.	2. DC device - need integration time.
3. Good resolution.	3. Large number of array elements for resolution.
4. Sensitivity determined by lens size and size of smallest element.	4. Sensitivity determined by sampling rate, integration time, resolution and lens.
5. Sampled at signal peak determined by BB sensor.	5. High sampling rate needed to defeat background.
6. Low data rate.	

CONCLUSIONS

At present the state of technology of optical sensors for use on low altitude satellites is such that sensitive (10^8 watts) lightning detectors and locators can be flown on the Shuttle and future low altitude satellites. For synchronous altitude applications, the basic sensors would still be used but with different optical lens configurations, and sensitivity threshold will probably be about 10^9 watts.

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THE STATE OF TECHNOLOGY IN ELECTROMAGNETIC (RF) SENSORS (FOR LIGHTNING DETECTION)

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Martial A. Honnell

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ABSTRACT

This paper presents a brief overview of the radio-frequency sensors which have been applied to the detection, isolation, and/or identification of the transient electromagnetic energy (sferics) radiated from one or more lightning discharges in the atmosphere. The paper begins with radio frequency (RF) characteristics of lightning discharges, general RF sensor (antenna) characteristics, sensors and systems previously used for sferic detection, electromagnetic pulse sensors, and finally references containing extensive bibliographies concerning lightning.

INTRODUCTION

The purpose of this paper is to report the results of a literature search on radio-frequency (RF) sensors used in lightning detection, analysis, and location. It is apparent that the techniques and sensors, or antennas, employed are similar to those used in radio location, radio navigation, radio communication and radar. The sensors developed for the measurement of electromagnetic radiation from nuclear explosions are also similar to the lightning sensors.

Due to the fact that the sensors employed depend upon the characteristics of lightning to be determined, a brief discussion concerning lightning phenomena is included.

LIGHTNING RF CHARACTERISTICS

The electromagnetic (RF) energy or noise radiated by a lightning discharge process is dependent upon the physical lengths of the discharge channels, the magnitudes of the discharge currents and the rates at which they change. Long channels of return strokes with large currents varying relatively slowly produce most of their energy in the very-low-frequency (VLF) and extremely-low-frequency (ELF) ranges. Leaders having shorter nominal lengths and varying more rapidly radiate in the low frequency (LF) range. Shorter and more rapid discharges of various types contribute to radiated energy in the medium-frequency (MF), high frequency (HF), and even very-high-frequency (VHF) and ultra-high-frequency (UHF) bands.

From PHYSICS OF LIGHTNING
by D. J. Malan

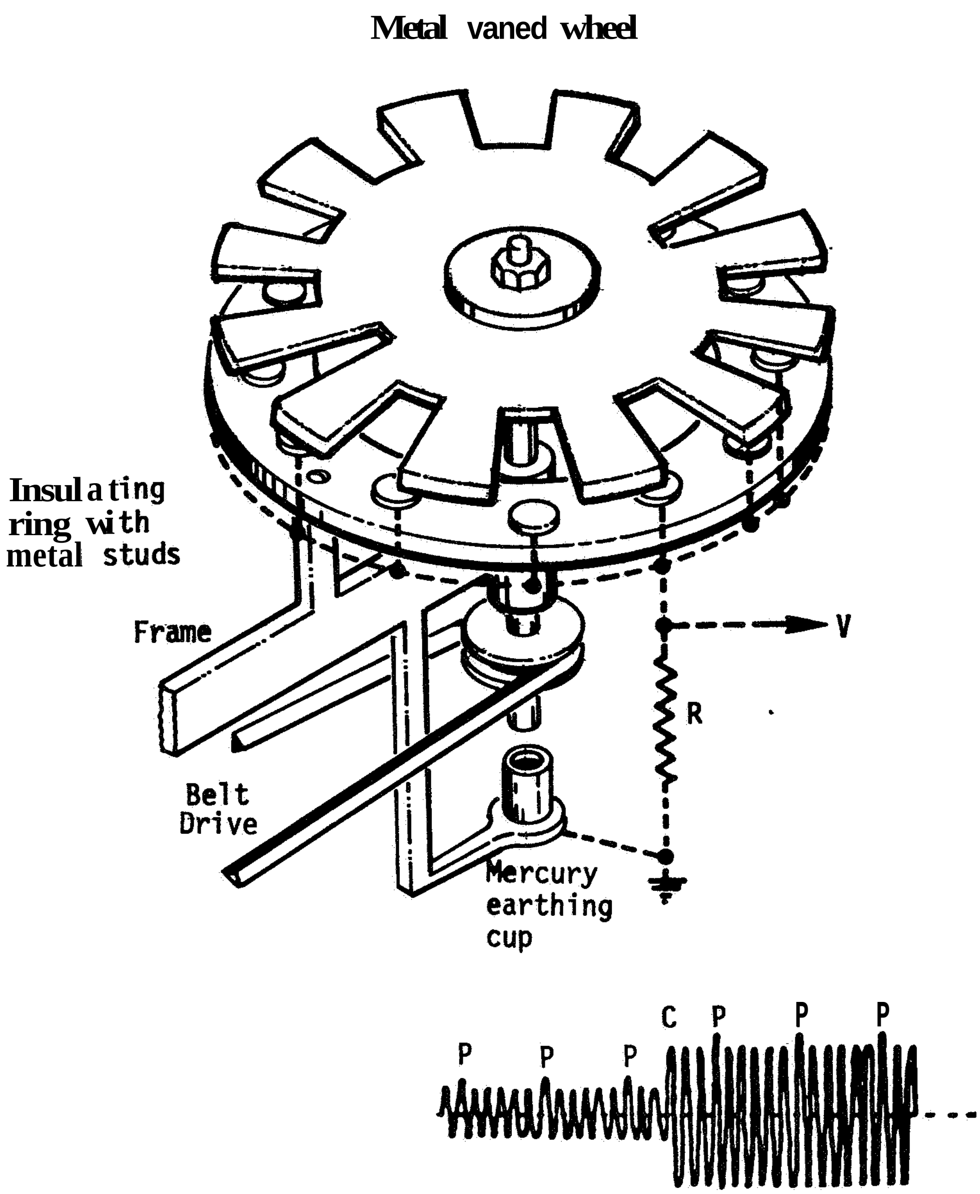

FIGURE 1. RECORD OF FIELD CHANGE C WITH POLARITY PIPS P.

From LIGHTNING, Vol. 1
edited by R.H. Golde, 1977

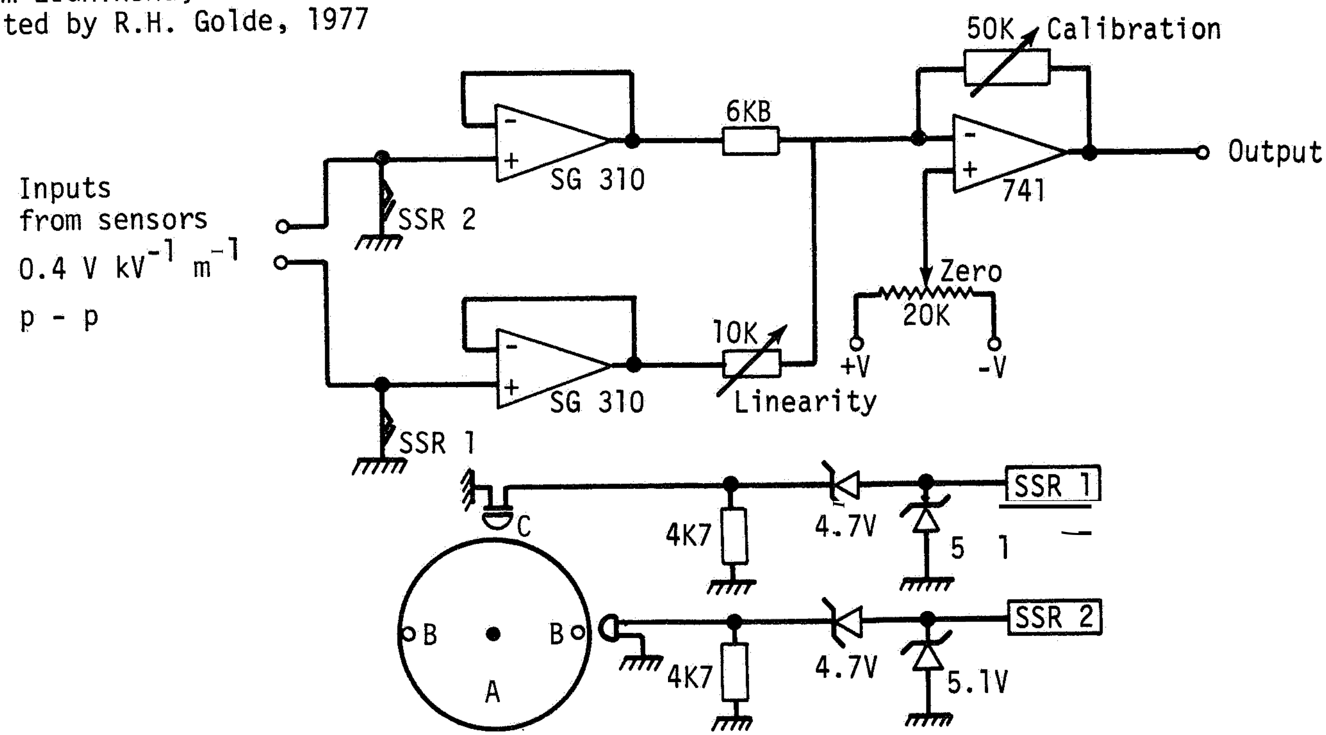

FIGURE 2. CIRCUIT DIAGRAM OF A FIELD MILL FOR ELECTROSTATIC FIELD-STRENGTH MEASUREMENT. SSR: SOLID STATE RELAY.

From LIGHTNING
by M.A. Uman

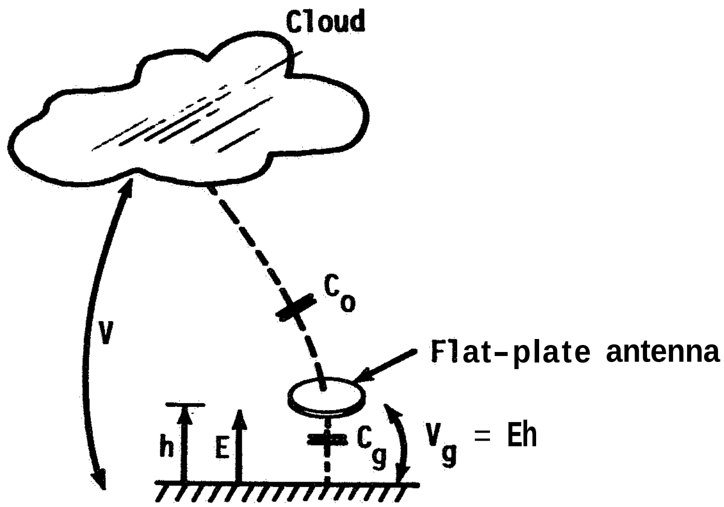

FIGURE 3a. FLAT-PLATE ANTENNA NOT ATTACHED TO ELECTRONICS.

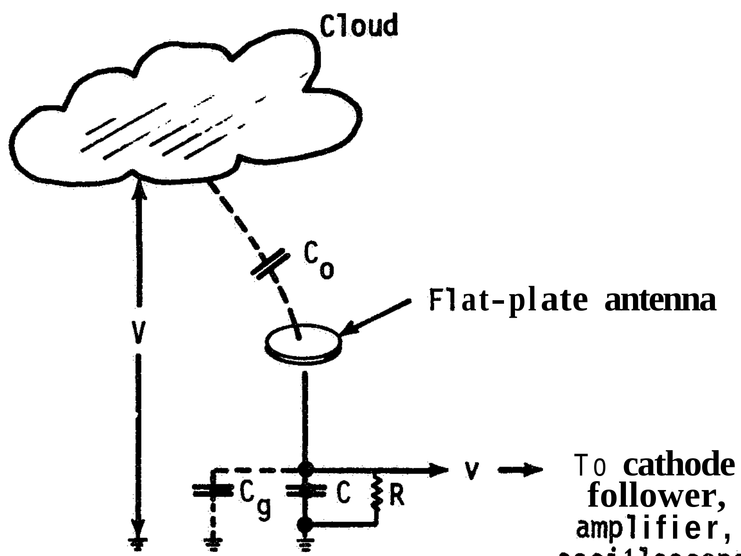

FIGURE 3b. FLAT-PLATE ANTENNA WITH ASSOCIATED ELECTRONICS.

From PHYSICS OF LIGHTNING
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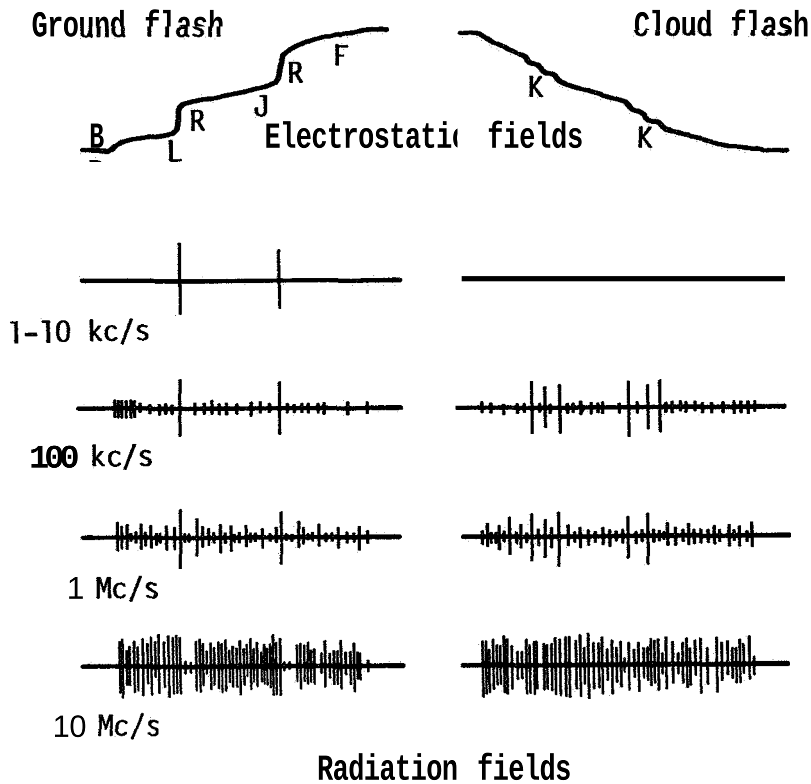


FIGURE 4. RADIATION PATTERNS OF GROUND AND INTRA-CLOUD FLASHES IN VARIOUS FREQUENCY RANGES.

From LIGHTNING, Vol. 1
edited by R.H. Golde, 1977

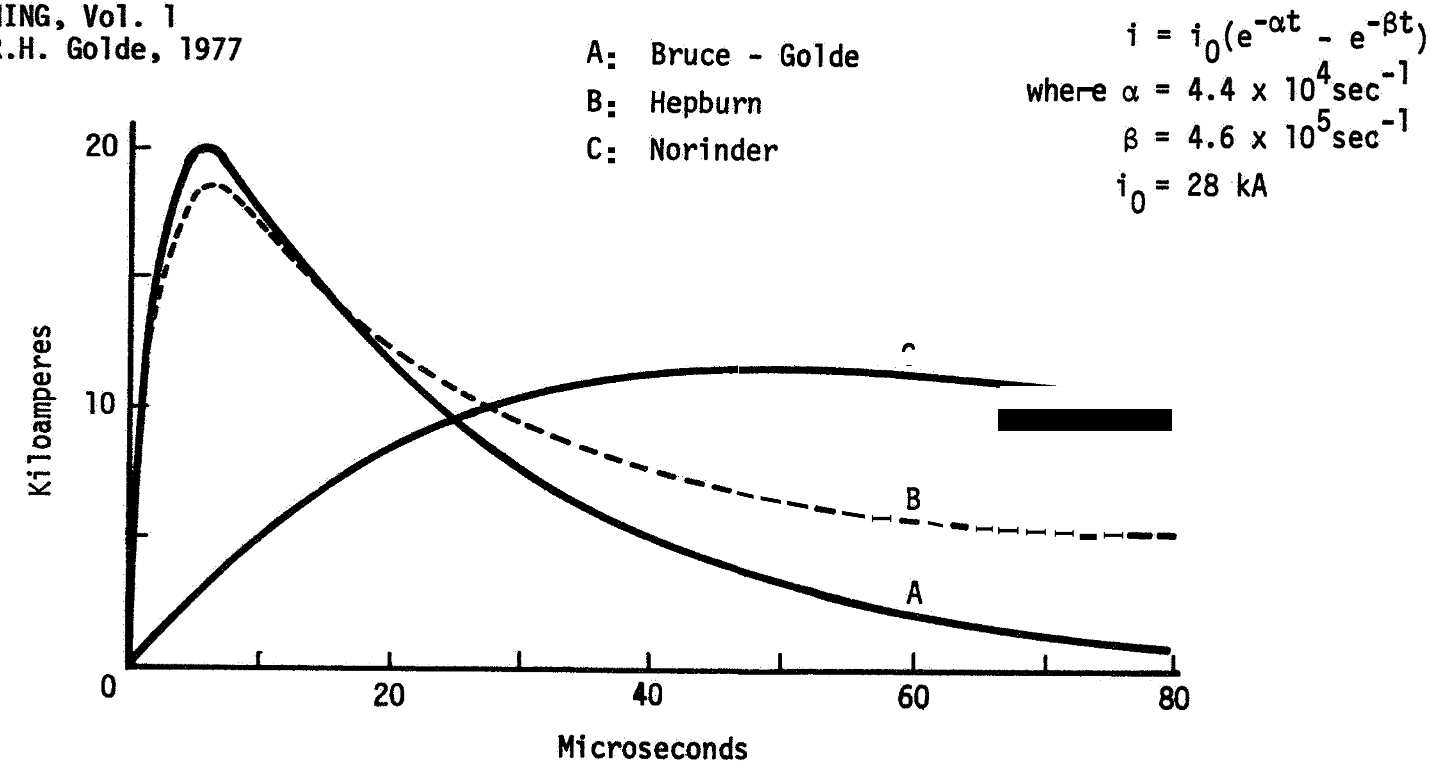


FIGURE 5 SUGGESTED THEORETICAL CURVES OF THE VARIATION OF RETURN STROKE CURRENT WITH TIME FOR A MODAL LIGHTNING FLASH.

From LIGHTNING, Vol. I
edited by R.H. Golde, 1977

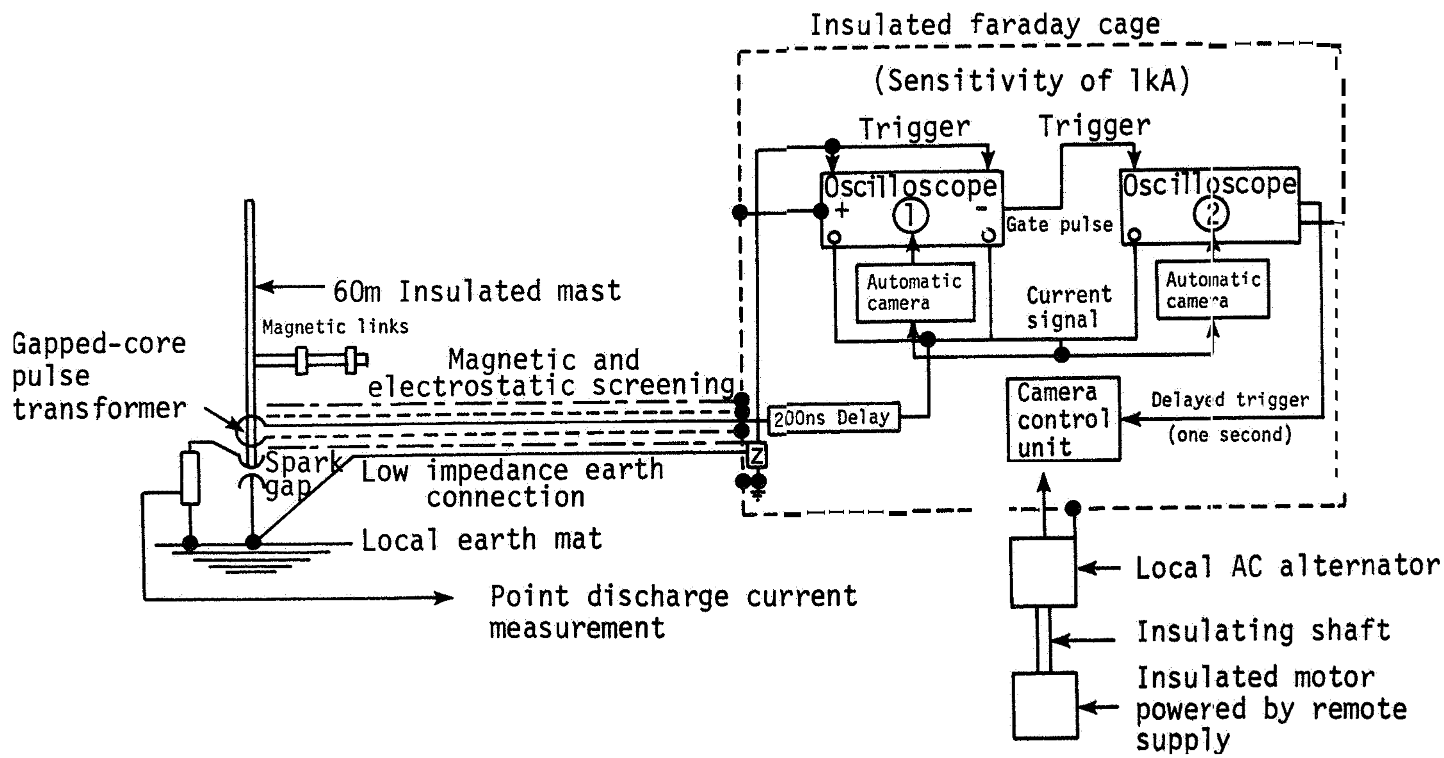


FIGURE 6 INSTRUMENTATION FOR THE AUTOMATIC RECORDING OF LIGHTNING CURRENT WAVE-FORMS OF STROKES TO A 60 m EXPERIMENTAL MAST. THE GAPPED-CORE PULSE TRANSFORMER HAS A FREQUENCY RESPONSE FROM 1 Hz TO 10 MHz (3 db POINTS), A DROOP OF 0.02% $m\ s^{-1}$ AND A SENSITIVITY (WHEN CORRECTLY TERMINATED) OF 1.5 VkA^{-1}. OSCILLOSCOPE 1 IS A DUAL-BEAM UNIT AND IS USED TO PROVIDE RECORDS OF THE INDIVIDUAL STROKE WAVE-FORMS FOR BOTH POSITIVE AND NEGATIVE CURRENTS. THE TIME BASE NORMALLY ADOPTED IS 100 μs. OSCILLOSCOPE 2 IS USED IN SINGLE-BEAM MODE AND RECORDS THE NUMBER OF STROKES AND TOTAL FLASH DURATION. THE TIME-BASE NORMALLY ADOPTED IS 1 s.

3

From PHYSICS OF LIGHTNING
by D.J. Malan

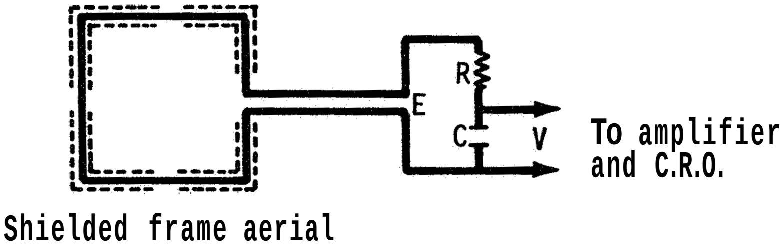


FIGURE 7. LOOP AND INTEGRATING CIRCUIT FOR DETERMINING CURRENT IN A FLASH FROM ITS MAGNETIC FIELD.

$$E = \frac{M}{4\pi\varepsilon_0 D^3} + \frac{1}{4\pi\varepsilon_0 c D^2}\left[\frac{dM}{dt}\right] + \frac{1}{4\pi\varepsilon_0 c^2 D}\left(\frac{d^2M}{dt^2}\right)$$

From LIGHTNING
by M.A. Uman

$$B = \frac{\mu_0}{4\pi D^2}\left(\frac{dM}{dt}\right) + \frac{\mu_0}{4\pi c D}\left(\frac{d^2M}{dt^2}\right)$$

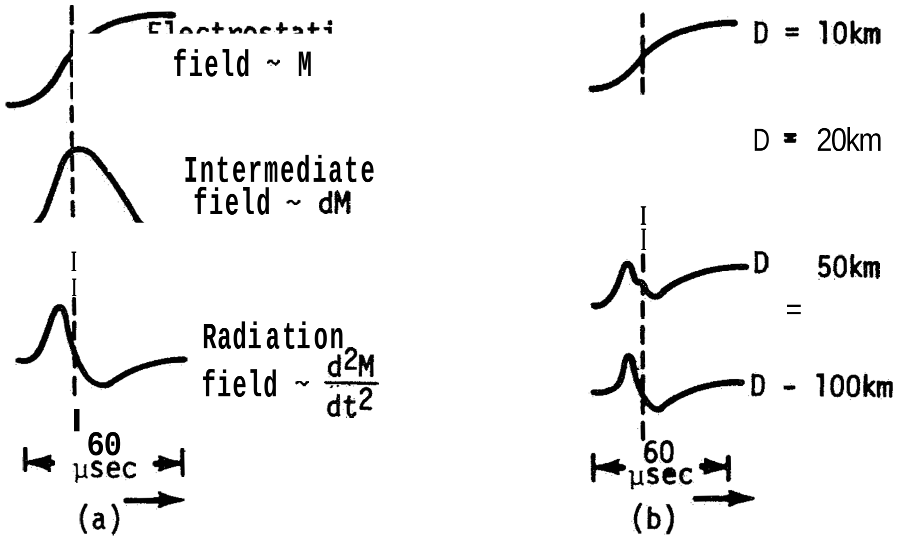


FIGURE 8. (a) ELECTRIC FIELD COMPONENTS VS. TIME FOR A RETURN STROKE. (b) TOTAL ELECTRIC FIELD INTENSITY VS. TIME AT SEVERAL DISTANCES FOR A RETURN STROKE.

Correlation of the received sferics with the charge transfer mechanism in the cloud-earth, cloud-cloud, or intracloud system is of prime importance. In order to correlate the cloud charge distributions with the received sferics, it is helpful to monitor the electrostatic field produced by these charge conglomerates. A common method of measuring this electrostatic field is the use of an array of field mills. The construction of a typical electrostatic field mill and associated electronic circuitry are shown in Figure 1 and 2 taken from Malan (1963, p. 42) and Golde (1977, p. 439), respectively. Another frequently used method for accurate determination of the electrostatic field change is the capacitive plate antenna. A pictorial view of such an antenna and its electrical representation have been given by Uman (1969, p.64) and are shown in Figure 3. A correlation between the electrostatic field and the sferics has been presented by Malan (1963, p. 133) and is reproduced in Figure 4. In the 1-10 kHz range, the only feature is a very pronounced evidence of the large return strokes denoted by "R" in the electrostatic fields. These features are again evident in the 100 kHz range but additional details are added from some of the other charge transfer processes denoted by "B", "L", "J", and "F". At 1 MHz, more amplitude relative to the large return stroke amplitude is added to the signal from these same processes. Finally, almost continuous energy emission occurs at 10 MHz, except it is curiously absent during the return stroke.

Observation of the temporal behavior of the sferic at different ranges from the source suggests a simplified model for prediction of the EM radiation from the return stroke current. Malan (1963, p. 100) presents a composite view of the return stroke current as a function of time in Figure 5. The equation for this current and nominal values of the parameters for the current are also shown. An instrumentation system for the actual determination of return stroke current waveforms is taken from Golde (1977, p. 456) and is shown in Figure 6. Another indirect scheme for determining the current waveform is by measurement of the magnetic field induced in a closed (shielded) loop. Such a loop and its accompanying integrating electrical circuit are shown in Figure 7 (Malan, 1963, p. 96). A mathematical model of this return stroke current has been presented by several investigators. Figure 8 obtained from Uman (1969, pp. 61, 62) illustrates the equations and the resulting field and its components at successive ranges. It should be pointed out that the quantities in the brackets in the equations for E and B represent the "retarded" moment and its derivatives, and consequently it has an implied delay time $(t - D/c)$. The dependence on range of each term in the equation for the electric field is seen to be D^{-3}, D^{-2}, and D^{-1} for the electrostatic, intermediate, and radiation fields, respectively. The illustrations below the equations vividly portray the dependence of the total field on the range from the source. Most measurements of sferics are made in the far zone at distances greater than one-sixth of a wavelength from the source. Another important characteristic of the sferic is its frequency-amplitude variation. A plot of peak field intensity versus frequency has been given by several authors. Most recently

Oh (1969, p. 126) has provided a plot of the spectral amplitude distribution of sferics which is shown in Figure 9. These data are seen to have a maximum near 5 kHz and then follow a nearly inverse frequency relationship over more than four decades with a possible additional roll-off to $f^{-5/2}$ near 100 MHz.

A comparison of these EM emissions with those from other sources has been published by Golde (1977, pp. 374, 378). The graph shown in Figure 10 represents typical relative values for ambient noise produced by man and by atmospherics for different times of day at an urban and rural location over a frequency range from 100 kHz to 100 MHz. A most interesting table also appears in Figure 10 comparing a peak sferic signal arriving at a satellite at two different orbit altitudes to the cosmic background noise at three separate frequencies. It should be emphasized that this table indicates significant signal-to-noise problems at synchronous altitude (37,000 km) for VHF and higher frequency bands.

Finally, it is of interest to ask what is the global distribution of lightning discharges. This is certainly one of many questions which could use further attention; however, one satellite (OSO-5) mission has provided some data using optical detection. Herman, et. al.(1973, p. 451) presented the illustration shown in Figure 11. It is apparent that these data suggest higher occurrence of lightning over large land mass areas than over open ocean areas. A higher density for the subtropical areas is apparent also. It is possible that sferic detection from satellite orbit might support the general conclusions of this optically obtained data.

RF SENSOR CHARACTERISTICS

In providing an adequate description for the design of RF sensors, specifications should be presented in standard or accepted terms. Several of the more important parameters in RF sensor (antenna) design are field patterns, gain (or directivity), effective area or length, bandwidth, beamwidth, field response (E or H), and polarization. Depending on the intended purpose of the RF sensor, several or all of these parameters must be identified prior to a choice of a specific sensor type.

SFERIC DETECTION

The term "detection" usually implies more than just the mere recognition that a lightning discharge event has occurred. Most often it includes an attempt to determine direction and range of the sferic source as well as application of various signal analysis techniques to extract pertinent spectral or temporal features from the sferic signal. Methods to accomplish these objectives have been suggested and used by a number of investigators. These methods may be separated into two main categories - active and passive.

From MEASURED AND CALCULATED SPECTRAL AMPLITUDE DISTRIBUTION OF LIGHTNING SFERICS by L.L. Oh, IEEE Trans EMC, Vol. EMC-11, No. 4, November 1969

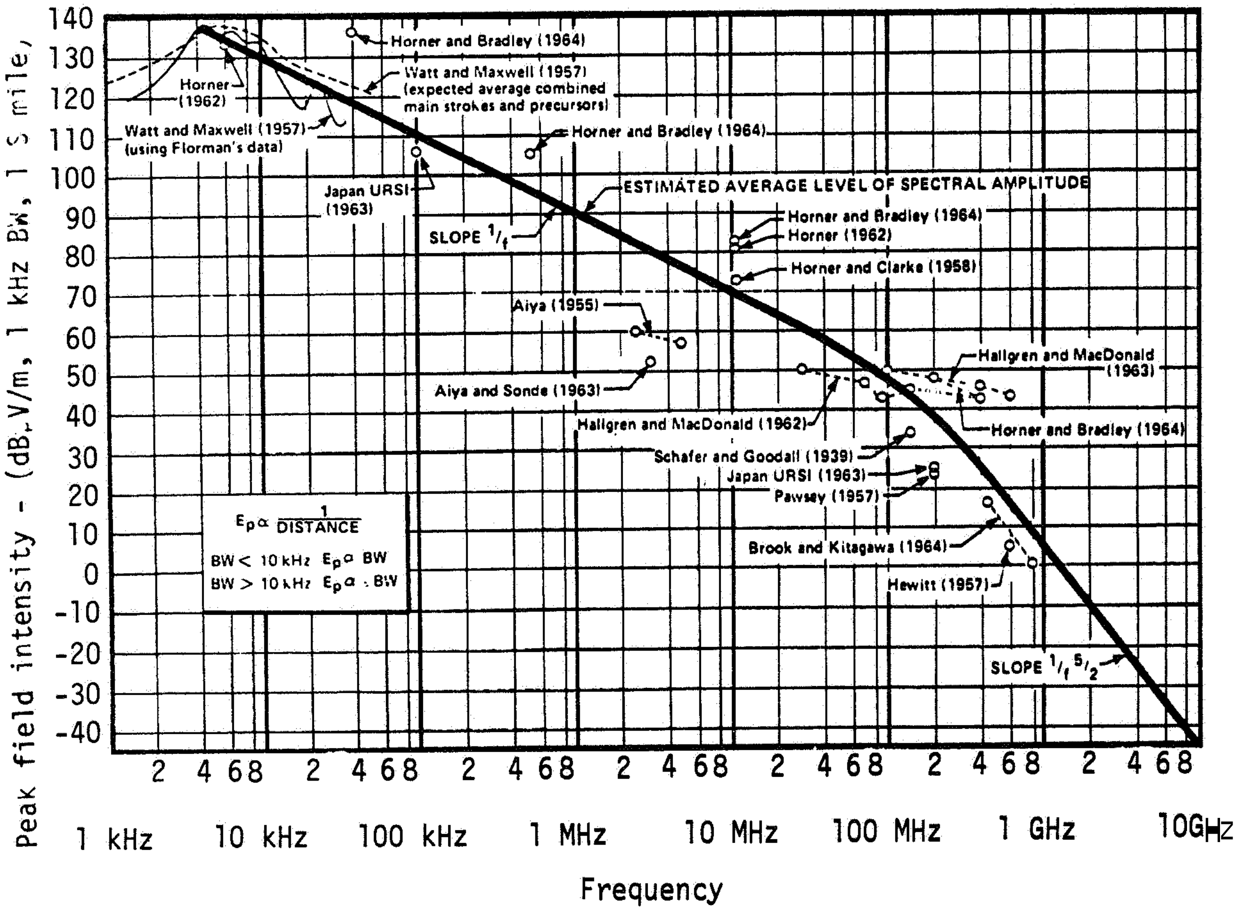


FIGURE 9. SPECTRAL AMPLITUDE DISTRIBUTION OF SFERICS.

From LIGHTNING, Vol. 1
edited by R.H. Golde, 1977

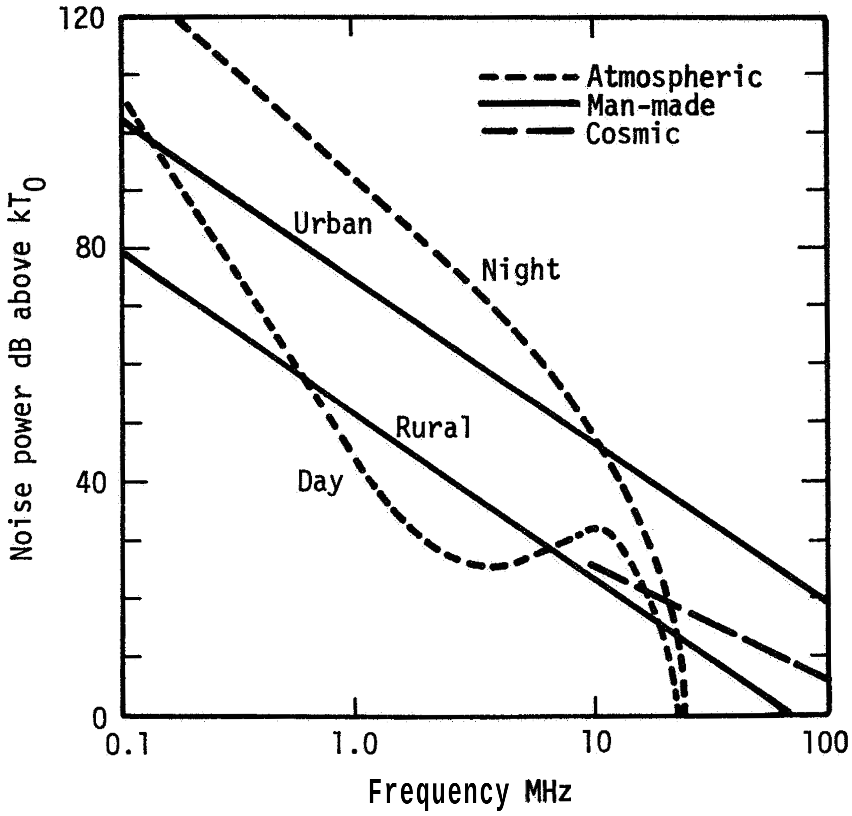


FIGURE 10. SOURCES OF RADIO NOISE.

Field strengths at satellite altitudes

(μVm^{-1} in 1 MHz bandwidth)

	Altitude--1,000 km Frequency			Altitude--100,000 km Frequency		
Source	10 MHz	30 MHz	100 MHz	10 MHz	30 MHz	100 MHz
Individual lightning flash	2×10^3	5×10^2	10^2	20	5	1
Cosmic noise background	10	10	$\lesssim$	10	10	$\lesssim$

From RADIO ASTRONOMY EXPLORER (RAE) I
OBSERVATIONS OF TERRESTRIAL RADIO NOISE
by J.R. Herman, J.A. Caruso and R.G. Stone,
Planet. Space Sci. 1973, Vol. 21, pp. 443-446

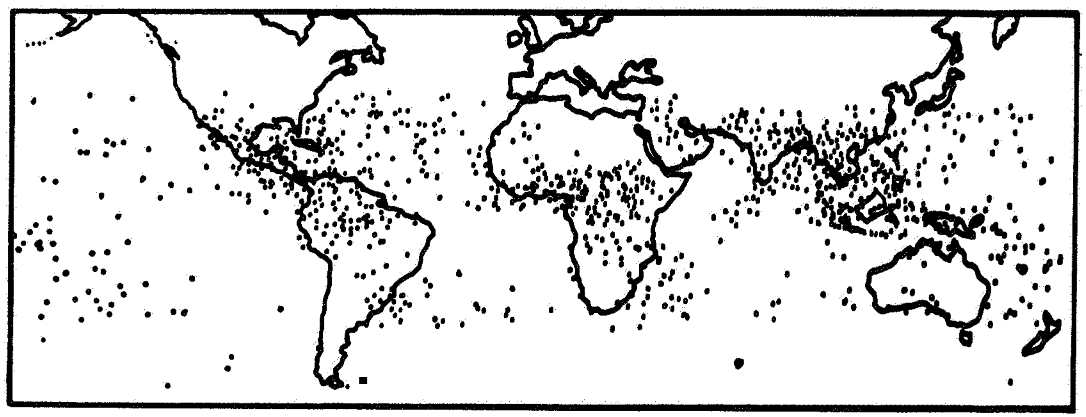


FIGURE 11. DISTRIBUTION OF NIGHT-TIME LIGHTNING STORM COMPLEXES OBSERVED BY PHOTOMETERS ON BOARD SATELLITE OSO-5. (REF 15)

Active systems utilize an interaction of a known transmitted RF signal with electrical or acoustical phenomena associated with the discharge. In the strictest sense, these systems should not be referred to as sferic detection systems but are included in these considerations because of the wealth of information they can yield about the sferic source. The most widely used active methods employ radar techniques. These rely on the radar return either from the heavy moisutre concentration in a cloud which often correlates well with position of the discharge or from an actual reflection of the radar signal from the ionized channel generated in the discharge. Another method recently employed by Hung (1978) is referred to as an ionospheric doppler sounder which appears promising as a severe weather indicator.

The passive systems utilize direct monitoring of the EM emissions from the various charge movements in the region of interest.

The reception of sferics (in the far radiation zone) is accomplished with a variety of sensors and systems. The sensors may be divided generally into electric types (monopoles, dipoles, linear elements) and magnetic types (loops). The systems may be divided into direction-of-arrival and time-of-arrival. One of the most widely used direction-of-arrival sferic detection systems is known as the cathode-ray direction-finder (CRDF) system. The sensors for such CRDF systems are commonly a pair of orthogonal loops as shown by Malan (1963, p. 155) in Figure 12 or pairs of orthogonal electric dipoles such as the Adcock arrays given by Terman (1943, p. 885) in Figure 13. In these systems the sensor (antenna) outputs are amplified and fed directly to a cathode ray oscilloscope for direction indication. These CRDF systems are utilized in multiple location schemes, and they have been used routinely and effectively for over fifty years in RF direction-finding applications. One effective system developed by Cianos, et. al. (1972, p. 1121) utilizing the time-of-arrival method for lightning detection is shown in Figure 14. Other investigators (see Figure 15, Murty and MacClement, 1973, p. 1401) have used similar systems with good success. An improvement of the fundamental time-of-arrival method was developed by Krider, et. al. (1976, p. 301). Their technique used time-gating to concentrate on only the initial portion of the return storke waveform. This system appears to have been well-received by the interested lightning detection community.

Lightning detection entered a new era with the launching of several orbiting satellites equipped with on-board RF sensors for terrestrial radio noise measurements. One of the first of these satellites was UK-3 (Ariel 111) which was placed in a near circular orbit at an altitude of 550 km. The frequencies of observation were 5, 10, and 15 MHz. The radio frequency noise observed by this satellite has been reported by Horner and Bent (1969, p. 527). Following this experiment closely, another satellite for terrestrial radio noise measurements was placed in orbit. This was the Radio Astronomy Explorer (RAE) I which orbited at about 6000 km. The RF measurements of RAE I were reported by Herman

a

From PHYSICS OF LIGHTNING
by D.J. Malan

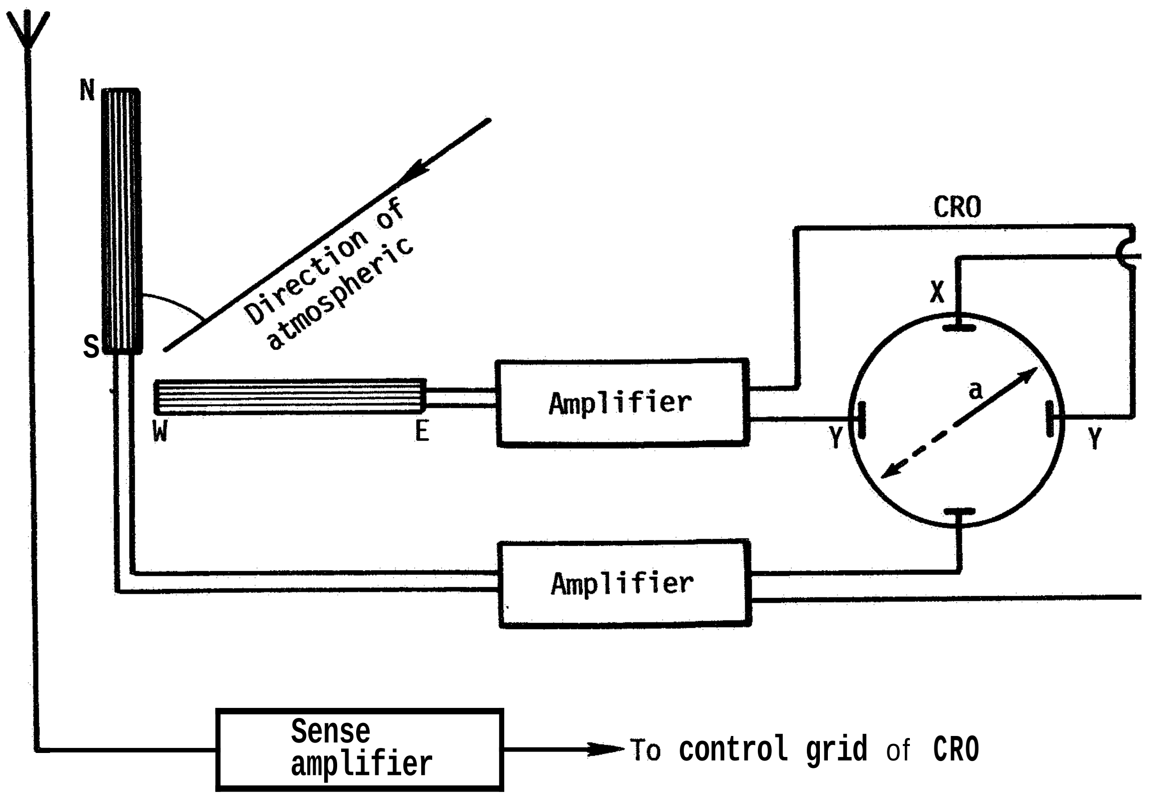
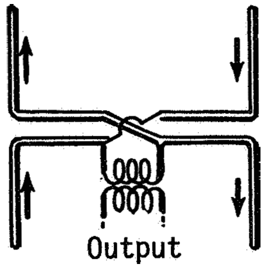
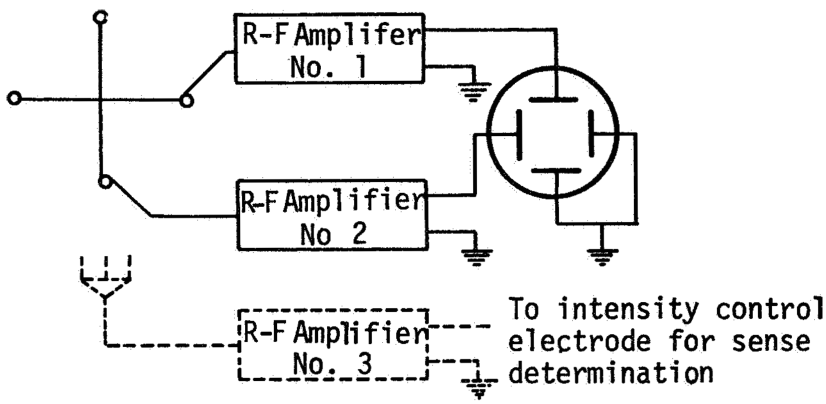


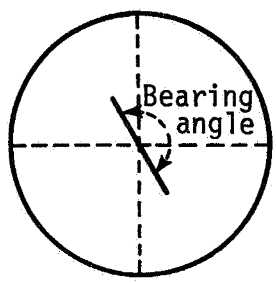
FIGURE 12. DIRECTION FINDING BY LOOP AERIALS NS AND EW AND CATHODE-RAY OSCILLOGRAPH.

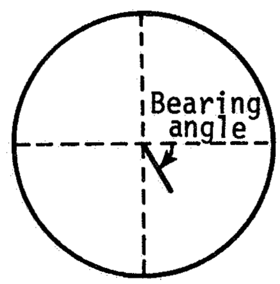


Terman's RADIO ENGINEERS HANDBOOK, pp. 880-883



(a) Schematic circuit





(b) Cathode-ray pattern without sense determination

(c) Cathode-ray pattern with sense determination

FIGURE 13. INSTANTANEOUS CATHODE-RAY DIRECTION-FINDER SYSTEMS.

From A TECHNIQUE FOR ACCURATELY LOCATING LIGHTNING AT CLOSE RANGES by N. Cianos, G.N. Oetzel and E.T. Pierce, Jr. of Applied Meteorology, Vol. 11, p. 1120.

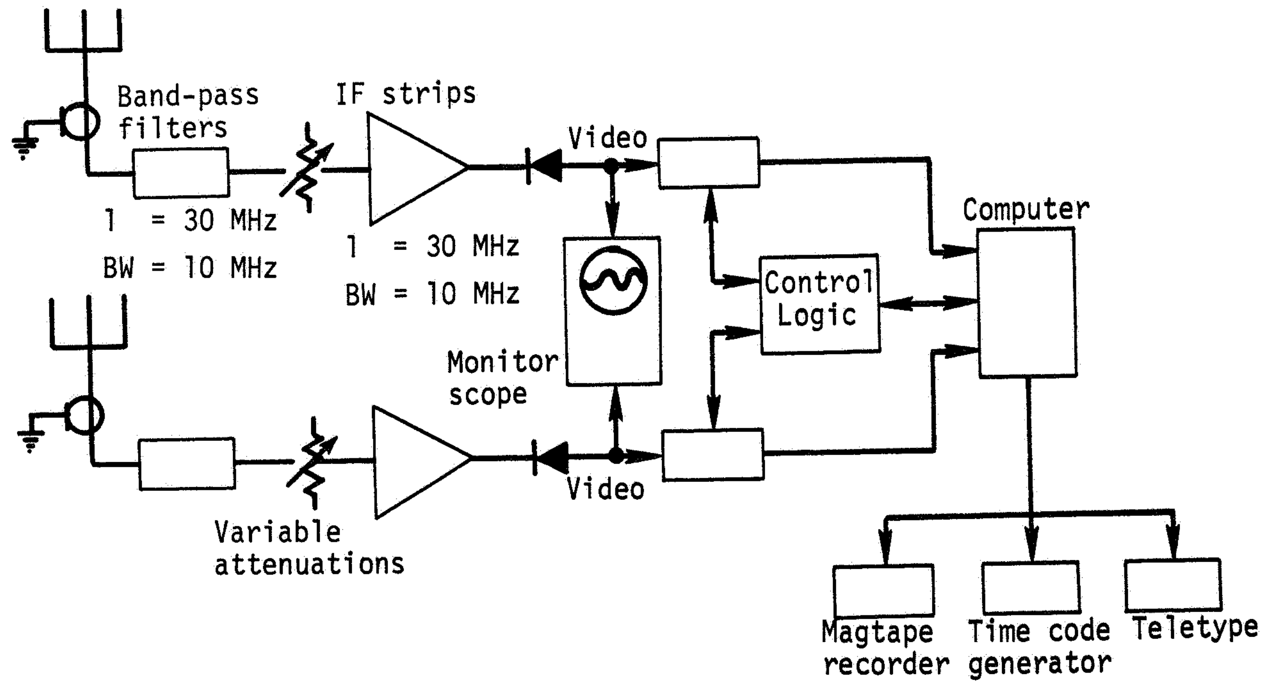


FIGURE 14. SIMPLIFIED BLOCK DIAGRAM OF LIGHTNING DIRECTION-FINDING EQUIPMENT.

From VHF DIRECTION FINDER FOR LIGHTNING LOCATION by R.C. Murty and W.D. MacClement, J. of Applied Meteorology, Vol. 12, p. 1401

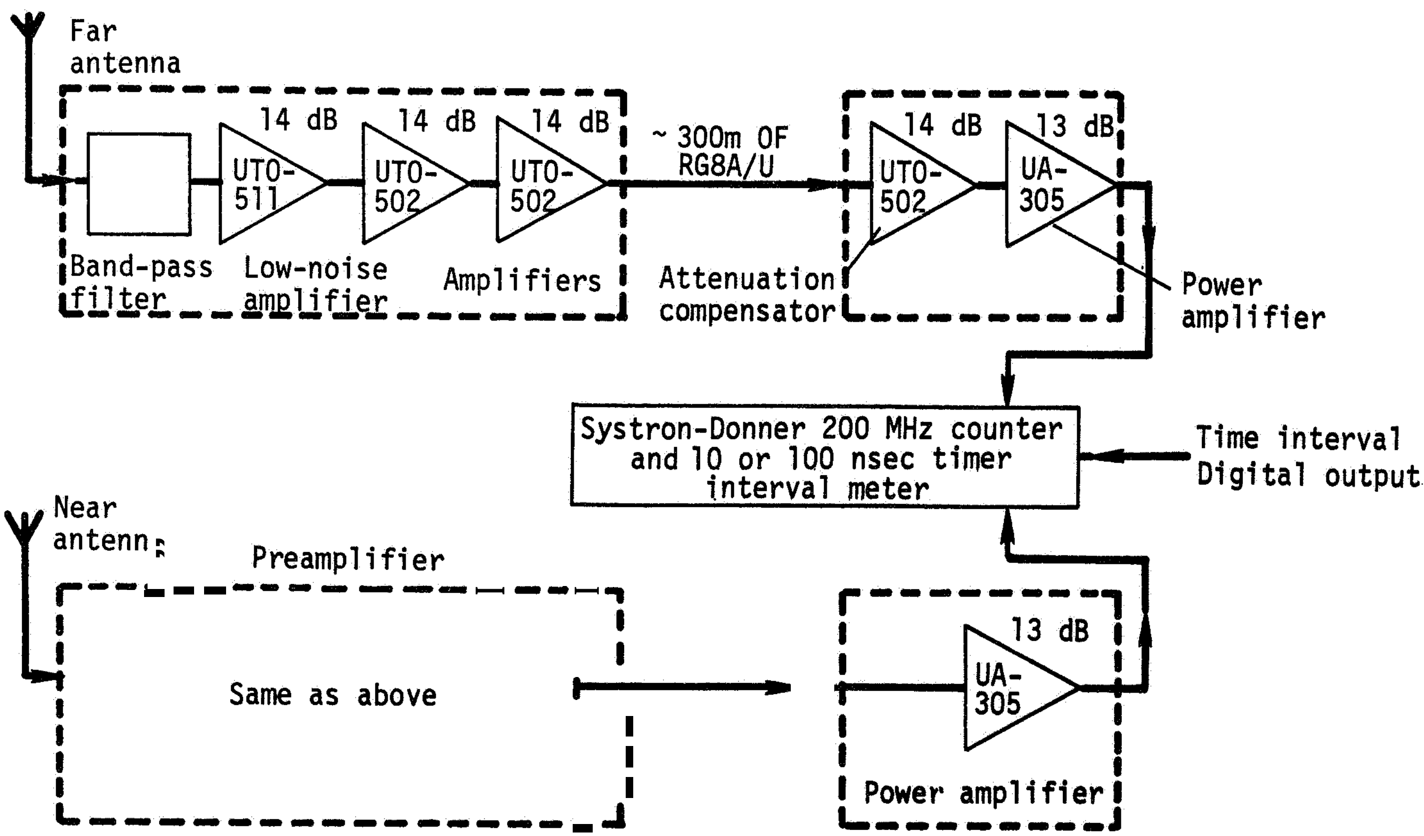


FIGURE 15. BLOCK DIAGRAM OF THE VHF DIRECTION FINDER

and Caruso (1973, p. 443). Figure 16 shows the deployment of the antennas of this satellite. About one year ago a Japanese satellite, Ionosphere Sounding Satellite (ISS-b), was launched with the objective of utilizing the ionospheric "iris" effect to monitor lightning activity in the HF band. This technique was proposed and discussed by Kirkwood (1965). The results of the ISS-b experiments are presented by Kuriki, et. al. (1978). Early this year (1979) another satellite, the Space Test Program P78-2 (SCATHA) was launched near synchronous orbit. Details of the HF monitor antennas and frequencies may be found in a SAMSO report (Stevens and Vampola, 1978).

RELATED TOPICS

Nuclear detonations radiate large amplitude, fast rise time (on the order of a few nanoseconds) impulsive electromagnetic fields, These transient radiations have been designated electromagnetic pulses (EMP). The descriptive electrical characteristics of EMP have many similarities to those generated by the lightning discharge. Sferic detection systems may be used to monitor these nuclear EM emissions; and systems specifically designed for EMP detection might also prove useful in sferic detection.

In recent years, considerable effort has been expanded toward simulation, detection, and prediction of the effects of these EMP emissions on power, communication and defense systems. As a result of these efforts, EMP sensors and sensor systems have been developed. In Table 1, three of the fundamental broadband sensors commonly used in the EMP field are presented along with a few of their pertinent sensor parameters.

TABLE 1

EMP SENSORS

Name	Field Response	Effective Area or Height	Risetime 10% to 90%
Multigap Loop, MGL-2B	B	10^{-2} m^2	1.2 ns
Parallel-Plate Dipole PPD-2A	E	2×10^{-2} m	< 1 ns
Hollow Spherical Dipole HSD-2A	D	10^{-1} m^2	< 2.7 ns

The excellent risetime and bandwidth characteristics of these sensors should make them useful for obtaining lightning signatures and for sferic detection. In addition to field sensors:, the EMP investigations have led to the development of broadband radiators for the simulation of these impulsive emissions. These broadband radiators are in the form of biconic antennas; impedance loaded monopoles, dipoles, and loops; and

From RADIO ASTRONOMY EXPLORER (RAE) I
OBSERVATIONS OF TERRESTRIAL RADIO NOISE
by J.R. Herman, J.A. Caruso and
R.G. Stone, Planet. Space Sci. 1973,
Vol. 21, pp. 443-446

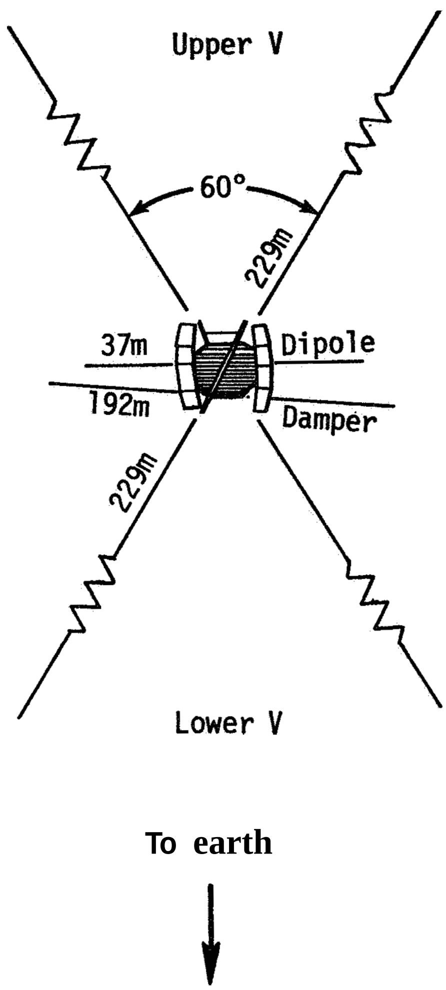


FIGURE 16. RAE-I ANTENNA BOOM DEPLOYMENT.

long wire traveling-wave antennas. These structures could also prove useful for simulation of sferics. The transient EM field technology developed in EMP studies may have application to lightning investigations.

CONCLUSIONS

The RF sensors most commonly used in lightning studies are the field mill and capacitor plate antenna for electrostatic field measurements; the vertical antenna, the loop antenna, and the Adcock antenna for lightning radiation measurements. Most measurements made are of the vertically polarized radiation field. Antennas used for low-frequency measurements are electrically short and, therefore, have broadband characteristics and low sensitivity. Directivity is obtained through the use of crossed loop or crossed Adcock antennas. At VHF and higher frequencies, directional antennas with high sensitivities are available. Although the radiated energy from lightning is low at VHF frequencies, the high gain and directional characteristics of the antennas will assist in obtaining a useable signal-to-noise ratio.

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THE GEOGRAPHICAL DISTRIBUTION OF LIGHTNING
— FORESTRY AND RANGE REQUIREMENTS AND INTERESTS —

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Office of Scientific Systems Development

United States Department of Interior
Bureau of Land Management

Nearly half of the wildfire in the western United States and Alaska is lightning-caused. Land managers in government and the private sector have an ongoing interest in the geographical distribution of lightning and the need for near real-time lightning ground discharge positions. At present, lightning occurrence maps are based on the "Thunderstorm Day," or a day in which one hears thunder. This statistic is heavily biased by the population density of an area. In Alaska it has been noted that nearly 5,000 lightning ground discharges have been recorded by detection equipment within 200 miles without hearing thunder at the detection station in Fairbanks. It is of particular interest to fire managers to be able to plan initial fire attack bases based on fire occurrence, resource valuation, population density and lightning distribution. Present lightning distribution maps are inadequate for this purpose.

In an attempt to reduce the response time of the initial attack forces to lightning-caused fire, the Bureau of Land Management, U.S. Department of Interior, in conjunction with the University of Arizona's Institute of Atmospheric Physics has developed a lightning detection system that effectively locates accurate directions to lightning discharges to over 200 miles from the detection equipment. Azimuth accuracy to + 1" yields a potential accuracy of a few miles at the system maximum range when a group of systems are incorporated in a network to allow cross vectoring of the azimuth information.

The BLM, University of Arizona System senses electromagnetic radiation in the 10 kHz frequency range on crossed magnetic loops and a flat plate electric field antenna. Pulse shape discrimination provides rejection of noise and intercloud lightning discharge signals.

The electric field sensed waveform provides additional polarity information for intercloud discharge rejection.

This system was first tested in Alaska in 1975. Since that time, further development and operational testing has led to the implementation of wide area networks. The system outputs are displayed on X - Y plotters, digitalized and printed, as well as transferred from station to station for manual and automatic cross vectoring for strike position determination.

For the 1979 fire season BLM will implement an eight station network in Alaska that will cover virtually all of the lightning-caused fire areas in the state. In the western United States, BLM and the U.S. Forest Service will implement an eighteen station network that will cover approximately 85 percent of the eleven western states. (See Figures 1 and 2.)

For the first time, large scale ground discharge lightning distribution information will be available. This system could provide excellent "ground truth" for a satellite lightning system and combining the two data sets would yield the ratio of lightning ground discharges to intercloud discharges.

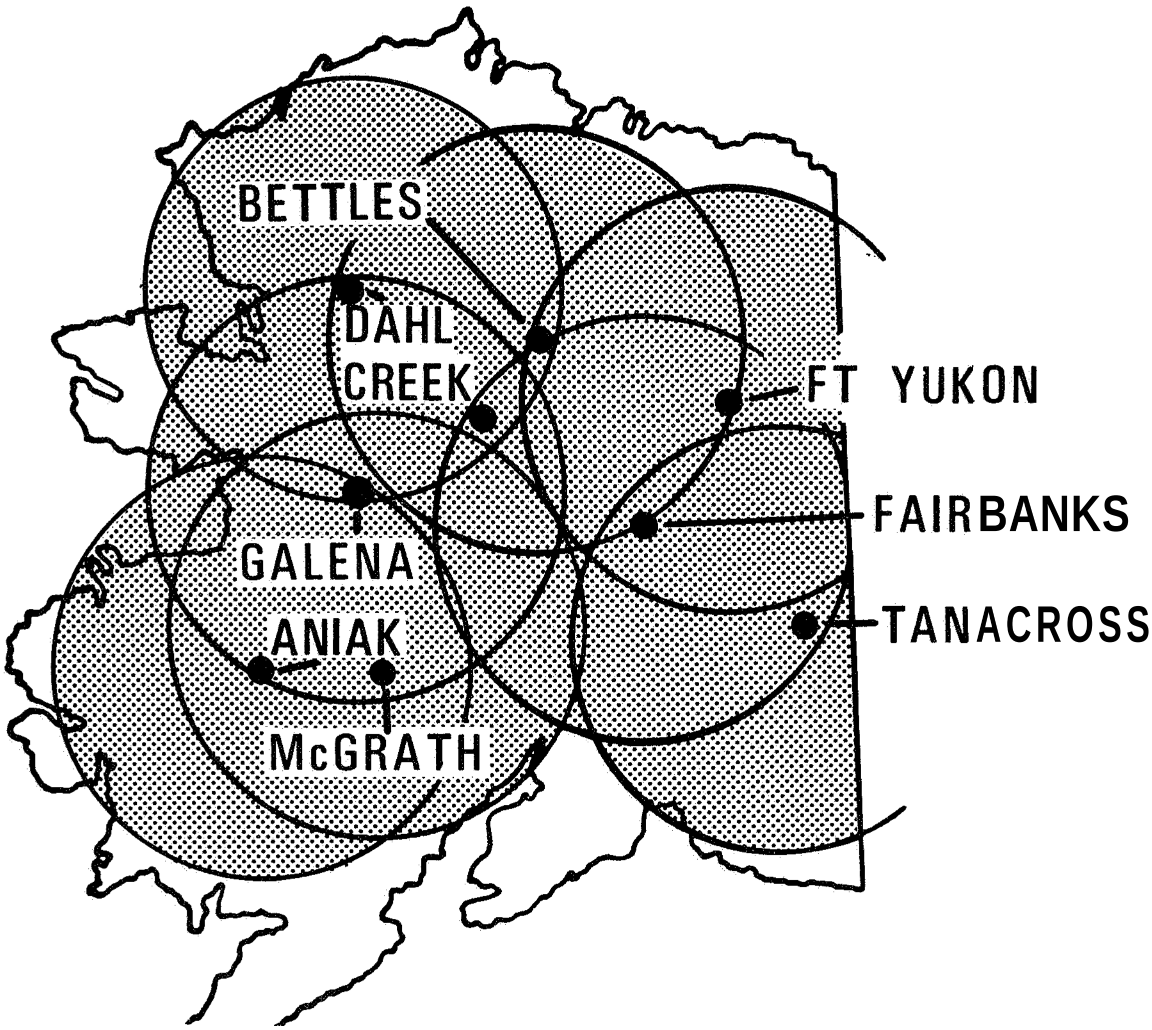


FIGURE 1 LIGHTNING DETECTION SYSTEM COVERAGE FOR ALASKA (1979)

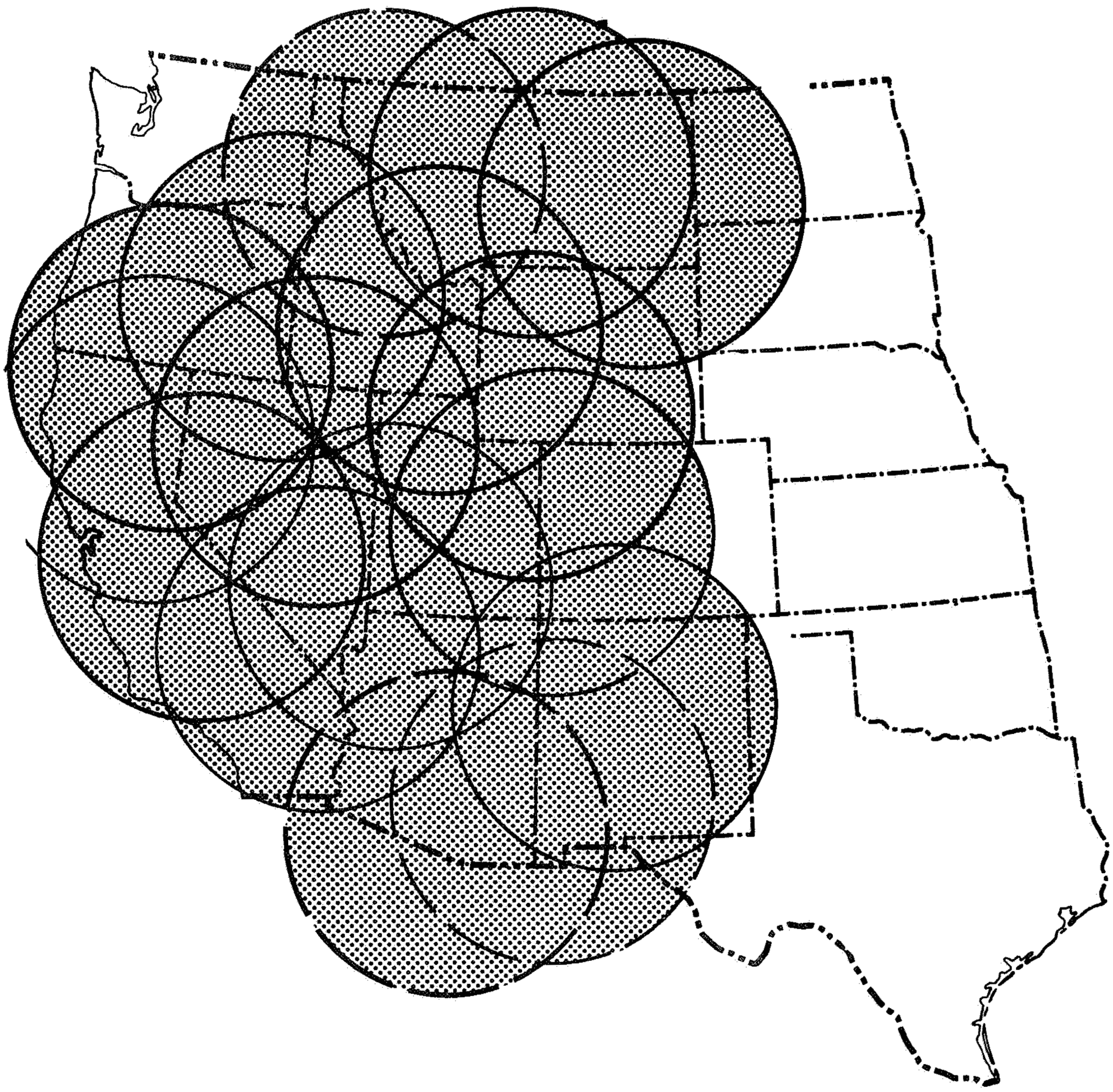
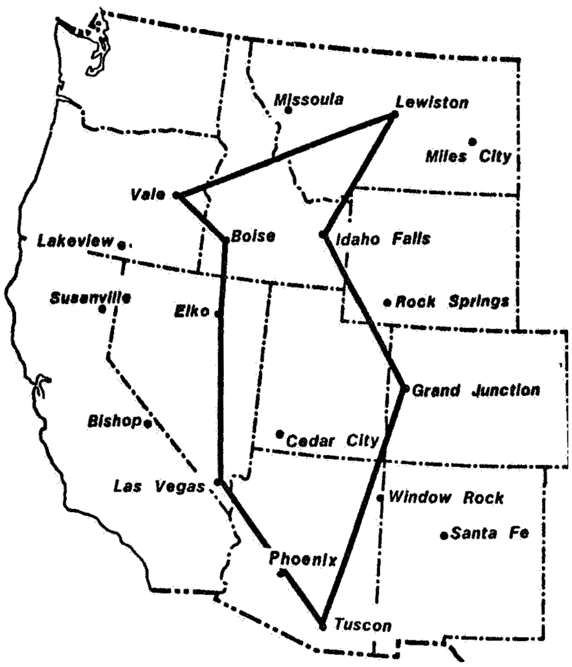
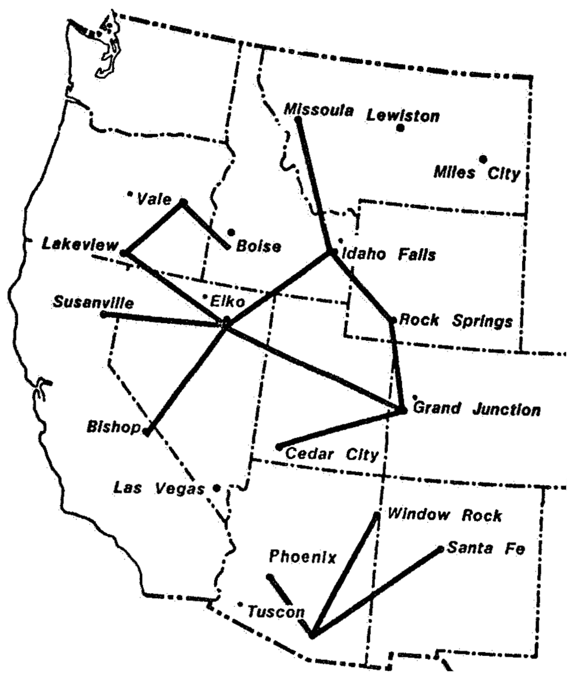


FIGURE 2. **LIGHTNING DETECTION SYSTEM COVERAGE FOR WESTERN UNITED STATES (1979).**

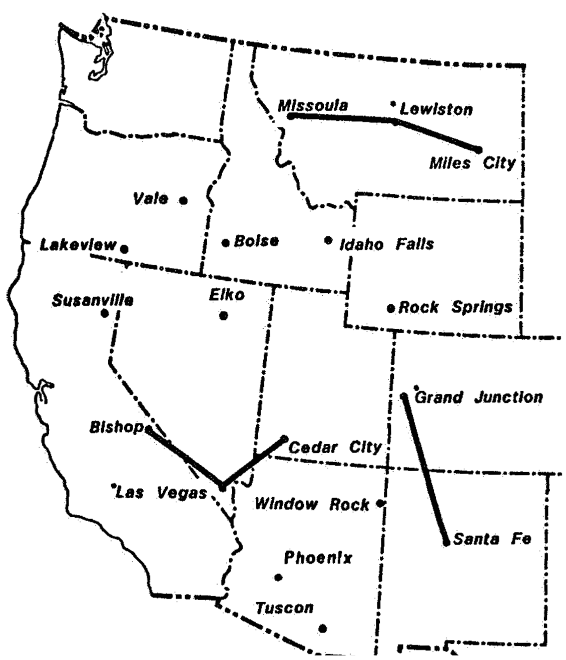


ADMINISTRATIVE NET
Half Duplex,
NO Call TTY, 110B



AUTOMATIC
CORRELATION NET
Full Duplex, 3008

*Automatic Correlators



HAND
CORRELATION NET
Half Duplex,
No Call TTY, 3008

*Hand Correlation
Stations

FIGURE 3. **COMMUNICATION INTERCONNECT FOR THE 1979 LIGHTNING DETECTION NETWORK.**

THE COMMERCIAL REQUIREMENTS AND INTERESTS OF THE POWER INDUSTRY

Robert A. Frech

Florida Power and Light Company

The electric utility bases its design for service reliability on the number of lightning strokes it may experience. At present time this is determined from the isokeraunic level of the area to be served. The isokeraunic level as defined, as the number of thunderstorm days, is a poor measure of lightning activity. Current thinking considers a higher lightning stroke density per thunderstorm day in the lower latitudes. A well known research project, financed by the Edison Electric Institute, was known as "The Pathfinder" (formally named "Mechanism of Lightning Flashover"). Approximately 4600 recording instruments were installed on 400 miles of transmission lines during a period from 1962 to 1971. The recommendations made in the final report of this project included the following: "Additional research is needed in the general area of "lightning severity" measures. Among these are:

Thunderstorm days (T.D.) (Poor)
Thunderstorm hours (T.H.) (Better)
Ground flash density (G.F.D.) (Best)
Distribution of current amplitudes
Distribution of current-time wave shapes."

There has been very little progress made since then. An intensive lightning study is now being made in the Tampa Bay Area. This study is backed by the Department of Energy and the three electric utilities in the area. Current-time wave shapes on short distribution lines are being recorded on 28 instruments. A ground stroke locator is in use and a two mile section of line has recording provisions for visual, electrical and magnetic field strength observations. Also, nine stroke counters developed in South Africa to register disturbances received in the radio broadcast band are being evaluated for determining ground flash densities. These counters have a limited range of 20 km (12.5 miles) and cannot distinguish between cloud-to-ground and cloud-to-cloud lightning strokes. The cost of the counters is relatively inexpensive, whereas the ground stroke locator has a high initial operating cost. The locator uses a triangulating system in conjunction with a computer to obtain a grid printout. With approximately one-half degree accuracy the resolution power of the locator is limited to a moderate range.

A satellite, which could distinguish between cloud-to-cloud and cloud-to-ground lightning strokes, would be beneficial to the electric utility industry. Range would be practically unlimited. Resolution power would only be limited, I assume, by the design. This satellite project would be a major step in the understanding of lightning.

THE COMMUNICATIONS INDUSTRY'S REQUIREMENTS AND INTERESTS

Oley Wanaselja

Currently available lightning data include NASA Contract Number NASW-3133, "Lightning Protection for Traffic Control Systems"; Isokeraunic Map of the United States, "Mean Annual Number of Days With Thunderstorms," (Figure 1); and Lightning Activity at Cities in the United States: 1) Isokeraunic level, 2) Total flashes per year, and 3) Flashes to ground, derived from statistics of the World Meteorological Organization, Geneva, Switzerland, 1953, World Distribution of Thunderstorm Days Part I, WMO/OMN No. 21, TP6 (Table 1).

Telephone operating companies depend heavily on trouble record reports to establish effects of lightning damage on an existing communications plant. A trouble index of over two customer complaints per 100 stations per month may be cause for investigation by the plant manager and transmission and protection engineers. Some rural telephone companies accept trouble index rates of three or more per 100 stations per month as the norm. These troubles are often related to lightning effects

Of interest to the communications industry are the amplitude, waveshape, duration and frequency of lightning-originated voltage surges and transients on the communications network, including the distribution system and AC power supply circuits.

The cloud-to-ground lightning discharge and its characteristics are thought to be most meaningful. Of specific interest are peak current, waveshape, number of flashes, strokes per flash, and zone of influence.

The protection of communications in today's electronic world is a must. The degree of protection required is usually determined at the local level and is dependent on service and economic considerations. Accurate and meaningful lightning data at the local level (telephone district office) is necessary for a decision on the appropriate protection level. In addition to lightning, the protection engineer must consider other factors such as: AC induction, switching surges, ground potential rise, soil resistivity, bonding and grounding techniques, shielding and isolation, and exposure of the telephone loop.

IEEE Std. 465.1-1977 (Standard Test Specifications for Gas Tube Surge Protective Devices) suggests waveshapes of 8/20 5kA and 20kA and 10/1000 50 Amp and 500 Amp as representative for protective devices. REA in PE-80 "Specification for Gas Tube Surge Arresters" classifies

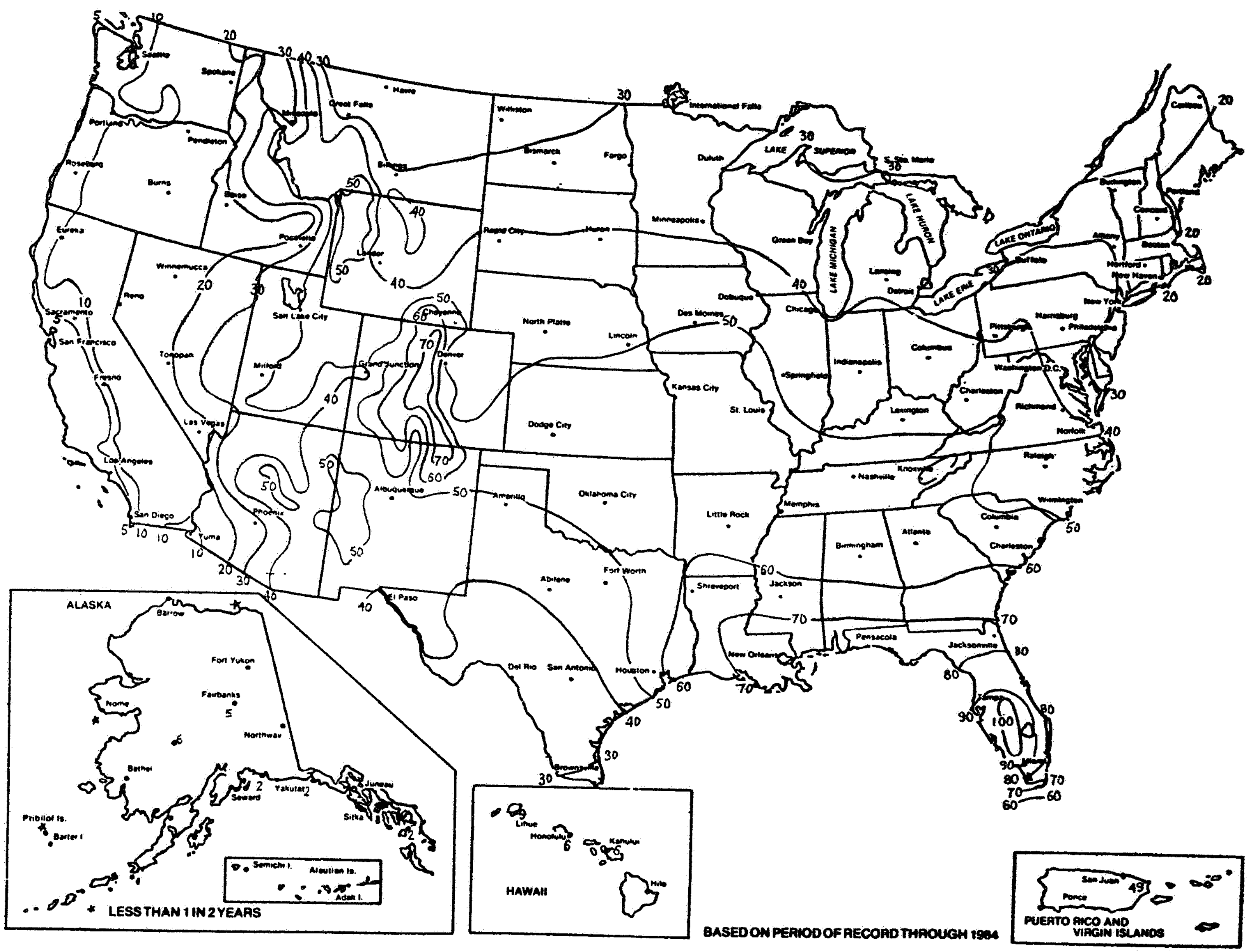


FIGURE 1

MEAN ANNUAL NUMBER OF DAYS WITH THUNDERSTORMS

Isokeraunic Map of the United States - Annual Number of Thunderstorm Days (Ty)

Lightning Activity at Cities in the United States

The following data is for use in estimating the number of lightning-related problems to be expected in particular cities Included are

1 The **Isokeraunic Level** which **is** the average number of days on which thunder is heard in **a** year
2 The **Total Flashes per Year** which is the total number of lightning flashes to be expected over areas **of 1** square kilometer at one square mile during a year
3 The **Flashes to Ground** which is the total number **of** lightning strikes expected to reach the ground in a year

This data has been derived from statistics gathered by the World Meteorological Organization (WMO) over many years (Reference 2) **As such,** it is average data and the experience in any individual year may differ somewhat from that predicted.

City	Isokeraunic Level	Latitude	Total Flashes per Year per KM²	Total Flashes per Year per mi²	Flashes to Ground per Year per KM²	Flashes to Ground per Year per mi²
ALABAMA						
Anniston	60	33°40'N	21 1	54 6	4 7	12 3
Birmingham	67	33°34'N	25 4	65 9	5 7	14.8
Mobile	64	30"41'N	23 5	60 9	4 8	12.4
Montgomery	54	32°18'N	17 6	45 6	3 8	9 9
ARIZONA						
Flagstaff	35	35°12'N	a 4	21 8	2 0	5 2
Phoenix	26	33°26'N	5.1	13 2	1 2	3.0
Prescott	43	34°39'N	12 0	31 0	2 8	7 2
Tucson	35	32°07'N	8 4	21 8	1 8	4.7
Winslow	34	35°01'N	8 0	20 8	1 9	4.9
Yuma	10	32°45'N	1 0	2.6	23	0.6
ARKANSAS						
Fort Smith	53	35°22'N	17 1	44 2	4.2	11.0
Little Rock	58	34°44'N	19 9	51 5	4 7	12 1
Texarkana	71	33°00'N	28 1	72 7	6 2	16.1
CALIFORNIA						
Bakersfield	3	35°25'N	0 1	0 3	0 04	0 1
Beaumont	9	33°56'N	0 8	2 2	0 2	0.5
Eureka	3	40°48'N	0 1	0 3	0 04	0 1
Fresno	4	36°46'N	0 2	0 5	0 04	0 1
Los Anyeles	3	33°56'N	0.1	0 3	0 04	0 1
Mount Shasta	14	41°17'N	1 8	4 6	0 5	1 3
Oakland	2	37°44'N	0.1	0 2	0 02	0.04
Red Bluff	9	40°09'N	0.8	2 2	0 2	0 6
Sacramento	4	38"31'N	0 2	0 5	0 04	0.1
San Diego	3	32"44'N	0 1	O S	04	0 1
San Francisco	2	37°45'N	0.1	0 2	0 02	0.04

TABLE 1b

City	Isokeraunic Level	Latitude	Total Flashes per Year per kM^2	Total Flashes per Year per mi^2	Flashes to Ground per Year per kM^2	Flashes to Ground per Year per mi^2
COLORADO						
Alamosa	51	37°26'N	16.0	41.4	4 1	10.6
Colorado Springs	68	38°49'N	26 1	67.5	7.0	18.2
Denver	44	39°46'N	12.4	32.2	3.4	8.9
Grand Junction	41	39°06'N	11.0	28.6	3.0	7 7
Pueblo	42	38°14'N	11 5	29.8	3.0	7.8
CONNECTICUT						
Hartford	27	41°44'N	5.4	14.0	1.6	4 1
New Haven	24	41°16'N	4.4	11.5	1.3	3.3
DELAWARE						
Wilmington	33	39°48'N	7.6	19.8	2 1	5.4
DISTRICT OF COLUMBIA						
Washington	35	38°51'N	8.4	21.8	2 3	5.9
FLORIDA						
Apalachicola	74	29°44'N	30 1	78.0	6.0	15.5
Daytona Beach	93	29°20'N	44.4	115.0	8.7	22.5
Fort Myers	91	26°35'N	42 8	110.8	7 6	19.7
Key West	57	24°35'N	19 3	50.0	3.2	8.3
Melbourne	88	28°06'N	40.4	104 7	7.6	19.7
Miami	70	25°49'N	27 4	71.0	4.8	12.4
Orlando	91	28°33'N	42.8	110.8	8 1	21 1
Pensacola	70	30°21'N	27 4	71 0	5.5	14.3
Tallahassee	78	30°26'N	32 9	85.3	6.7	17.3
Tampa	85	27°58'N	38 1	98.7	7 1	18.5
West Palm Beach	79	26°41'N	33 7	87.2	6 0	15.6
GEORGIA						
Albany	66	31°32'N	24.8	64.2	5.2	13.5
Athens	49	33°50'N	14 9	38.7	3.4	8.8
Atlanta	50	33°39'N	15.5	40.0	3.5	9.0
Augusta	41	33°28'N	11 0	28.6	2 5	6.4
Columbus	64	32°30'N	23.5	60 9	5.1	13.2
Macon	59	32°50'N	20 5	53.1	4.51	11 7
Rome	65	34°15'N	24.2	63.0	5.6	14.4
Savannah	53	32"01'N	17 1	44.2	3 7	9.5
Valdosta	69	30°53'N	26 7	69.2	5.5	14.3
IDAHO						
Boise	18	43°34'N	2 7	7 1	1 1	2.9
Lewiston	17	45°58'N	2 5	6 4	0.8	2 1
Pocatello	27	42°55'N	5 4	14 0	1 7	4.3
ILLINOIS						
Cairo	58	37°00'N	199	51 5	5 0	13.0
Chicago	37	41°47'N	9 3	24.0	2 7	7 1
Joliet	41	41°38'N	11 0	28.6	3.2	8.4
Moline	47	41°27'N	13.9	36 0	4 1	10.5
Peoria	47	40°40'N	139	36.0	3.9	10.2
Springfield	49	39"50'N	14 9	38.7	4 1	10.7

TABLE 1c

City	Isokeraunic Level	Latitude	Total Flashes per Year per kM²	Total Flashes per Year per mi²	Flashes to Ground per Year per kM²	Flashes to Ground per Year per mi²
INDIANA						
Evansville	50	38°02'N	15.5	40.0	4.0	10.4
Fort Wayne	41	41°10'N	11.0	28.6	3.7	8.2
Indianapolis	42	39°44'N	11 5	29.8	3.2	8.2
South Bend	48	41°42'N	14.4	37 4	4.2	11.0
Terre Haute	49	39°27'N	14.9	38.7	4 1	10.5
IOWA						
Burlington	56	40°47'N	18.7	48.6	5.3	13.8
Davenport	42	41°30'N	11.5	29.8	3.4	8.7
Des Moines	46	41°32'N	13.4	34.8	3.9	10.1
Dubuque	39	42°24'N	10.1	26.3	3.1	7.9
Sioux City	42	42°23'N	11 5	29.8	3.4	8.9
Sioux Falls	46	43°34'N	13.4	34.8	4.2	10.8
KANSAS						
Concordia	45	39"35'N	12.9	33.5	3.6	9.2
Dodge City	39	37°46'N	10.1	26.3	2.6	6.8
Goodland	44	39°21'N	12 4	32.2	3.4	8.8
Topeka	51	39°04'N	16.0	41 4	4.3	11.2
Wichita	54	37°38'N	17.6	45.6	0.5	11 7
KENTUCKY						
Lexington	44	38°02'N	12.4	32 2	3 2	8 4
Louisville	46	38°11'N	13.4	34.8	3 5	9.1
LOUISIANA						
Baton **Rouge**	78	30°25'N	32 9	85 3	6.7	17 3
Lake Charles	78	30°13'N	32 9	85.3	6 6	17 1
New **Orleans**	75	30°00'N	6 5	16 8	1 3	3.4
Shreveport	50	32°33'N	15 5	40 0	3.4	8.7
MAINE						
Caribou	21	46°52'N	3 5	9 2	1 2	3.2
Eastport	13	44°54'N	1 6	4 1	0 5	1 3
Portland	27	43°39'N	5 4	14.0	1 7	4 4
MARYLAND						
Baltimore	32	39°11'N	7 2	18 8	2 0	5 1
Frederick	24	39°20'N	4.4	11 5	1.2	3 1
MASSACHUSETTS						
Boston	20	42°22'N	3 3	8 4	1.0	2 5
Concord	24	43°12'N	4.4	11 5	1 4	3.5
Nantucket	15	41°15'N	2 0	5 2	0 6	1 5
Pittsfield	29	42°25'N	6 1	15 9	1 9	4 8
Salem	5	42°28'N	0 3	0.8	0.1	0.2
MICHIGAN						
Alpena	24	45°04'N	4.4	11 5	1 4	3 7
Detroit	32	42°24'N	7 2	18 8	2 2	5 6
Escanaba	33	45°48'N	7 6	19.8	2 5	6.6
Grand Rapids	39	42°54'N	10 1	26 3	3 1	8.0
Lansing	40	42°47'N	10.6	27 4	3 2	8.3
Marquette	25	46°34'N	4.8	12 3	1.6	4.2
Muskegon	33	43°10'N	7 6	19.8	2 4	6 1
Sault Ste Marie	24	46°25'N	4.4	11 5	1 5	3 9

a

TABLE 1d

City	Isokeraunic Level	Latitude	Total Flashes per Year per kM²	Total Flashes per Year per mi²	Flashes to Ground per Year per kM²	Flashes to Ground per Year per mi²
MINNESOTA						
Duluth	29	46°50'N	6.1	15.9	2 1	5.5
International Falls	28	48°36'N	5.8	14.9	2.1	5.4
Minneapolis	39	44°53'N	10.1	26.3	3.3	8.5
Rochester	40	44°00'N	11.0	27.4	3.3	8.4
St. Cloud	36	45°35'N	8.8	22.9	2.9	1.6
St. Paul	34	44°56'N	8.0	20.8	2.6	6.8
MISSISSIPPI						
Jackson	64	32°20'N	23.5	60.9	5.1	13.2
Meridian	64	32°20'N	23 5	60.9	5.1	13.2
Vicksburg	62	32°24 'N	22.3	57.7	4.8	12.5
MISSOURI						
Columbia	58	38°58'N	19 9	51 5	5.4	13.9
Kansas City	55	39°07'N	18.2	47 1	4.9	12.7
Springfield	59	37°14'N	20 5	53.1	5.2	13.5
St Joseph	54	39°46'N	17 6	45 6	4.9	12.6
St Louis	49	38°45'N	14 9	38.7	4.0	10.3
MONTANA						
Billings	33	45°47'N	7 6	19.8	2.5	6.6
Butte	43	46°00'N	12.0	31.0	4.0	10.4
Glasgow	27	48°11'N	5 4	14 0	1.9	5.0
Great Falls	29	47°30'N	6 1	15.9	2.2	5.6
Havro	23	48°31'N	4 1	10 7	1.5	3.9
Helena	31	46°36'N	6 9	17 8	2.4	6.1
Kalispell	22	48°11'N	3.8	9 9	1.4	3.5
Missoula	27	46°55'N	5 4	14 0	1.9	4.9
NEBRASKA						
Grand Island	50	40°58'N	15 5	40 0	4 4	11.5
Lincoln	47	40°52'N	13 9	36 0	4.0	10.3
Norfolk	53	41°59'N	17 0	44 2	5.1	13.1
North Platte	38	41°08'N	9 7	25 1	2 8	7.2
Omaha	39	41°18'N	10 1	26 3	2.9	7.6
Scottsbluff	48	41°50'N	14 4	37 4	4.3	11 1
Valentine	39	42°53'N	10 1	26 3	3 1	8.0
NEVADA						
Ely	31	39°17'N	6 9	17 8	1.9	4.9
Las Vegas	13	36°05'N	1.6	4 1	0 4	1.0
Reno	14	39°30'N	1.8	4.6	0.5	1.3
Winnemucca	11	40°54'N	1 2	3 1	0.03	0.9
NEW HAMPSHIRE						
Mount Washington	16	44°16'N	3 2	5 8	0 7	1.8
NEW JERSEY						
Atlantic City	23	39°22'N	4 1	10 7	1 1	2.9
Newark	27	40°42'N	5 4	14 0	1.5	4.0
Trenton	35	40° 13'N	8 4	21 8	2.4	6.1

TABLE 1e

City	Isokeraunic Level	Latitude	Total Flashes per Year per kM²	Total Flashes per Year per mi²	Flashes to Ground per Year per kM²	Flashes to Ground per Year per mi²
NEW MEXICO						
Albuquerque	47	35°03′N	13.9	36.0	3.3	8.5
Clayton	63	36°27′N	22.9	59.3	5.7	14.7
Raton	75	36°58′N	30.8	79.8	7.8	20.1
Roswell	45	33°24′N	12.9	33.5	2.9	7.5
NEW YORK						
Albany	23	42°45′N	4 1	10.7	5.4	3.2
Bear Mountain	28	41°50′N	5.8	14.9	1 7	4.4
Binghampton	31	42°05′N	6.9	17.8	2.0	5.3
Buffalo	29	42°56′N	6.1	15.9	1.9	4.8
New York City	31	40°46′N	6.9	17.8	2.0	5.1
Oswego	25	43°25′N	4.8	12.3	1.5	3.8
Rochester	27	43°07′N	5.4	14.0	1 7	4.3
Syracuse	30	43°07′N	6.5	16.8	2.0	5.1
NORTH CAROLINA						
Asheville	53	35°36′N	17 1	44.2	4.1	10.6
Cape Hatteras	40	35°15′N	10.6	27.4	2.5	6.5
Charlotte	46	35°14′N	13.4	34.8	3.2	8.2
Greensboro	50	36°05′N	15.5	40.0	3.8	9.8
Raleigh	41	35°52′N	11 0	28.6	2 7	7.0
Wilmington	46	34°14′N	13.4	34 8	3.1	8.0
Winston-Salem	46	36°07′N	13.4	34.8	3.3	8.5
NORTH DAKOTA						
Bismark	31	46°46′N	6.9	17.8	2 4	6.1
Devil's Lake	30	48°07′N	6.5	16.8	2 3	6.0
Fargo	29	46°54′N	6 1	15.9	2 1	5.5
Williston	25	48°09′N	4 8	12 3	1 7	4.4
OHIO						
Akron	38	41°02′N	9 7	25 1	2.8	7.2
Cleveland	35	41°24′N	8.4	21 9	2 4	6.3
Cincinnati	53	39°04′N	17 1	44 2	4 5	11.9
Columbus	40	40°00′N	10.6	27 4	2 7	7 6
Dayton	48	39°49′N	14 4	37 4	4.0	10.3
Sandusky	31	41°25′N	6.9	17.8	2.0	5.2
Toledo	35	41°34′N	8.4	21 8	2 5	6.4
Youngstown	36	41°16′N	8.8	22 9	2 5	6.6
OKLAHOMA						
Oklahoma City	45	35°24′N	12 9	33.5	3 1	8.0
Tulsa	58	36°11′N	19 9	51 5	4 9	12.6
OREGON						
Baker	16	44°50′N	2.2	5 8	0.7	1.9
Burns	14	43°35′N	1.8	5 0	0 5	1.4
Eugene	5	44°07′N	0 3	0 8	0 1	0.3
Medford	9	42°23′N	0.8	2 2	0 3	0 7
Pendleton	12	45°41′N	1 4	3 5	0 5	1.2
Portland	6	45°36′N	0 4	1 1	0 2	0.4
Roseburg	5	43°13′N	0.3	0 8	0 1	0.2
Troutdale	12	45°35′N	1 4	3 5	0 5	1.2

TABLE 1f

city	Isokeraunic Level	Latitude	Total Flashes per Year per kM²	Total Flashes per Year per mi²	Flashes to Ground per Year per kM²	Flashes to Ground per Year per mi²
PENNSYLVANIA						
Allentown	36	40°39'N	8.8	22.9	2.5	6.5
Curwensville	47	40°59'N	13.9	36.0	4.0	10.3
Erie	33	42''05'N	7.6	19.8	2.3	5.9
Harrisburg	33	40''13'N	7.6	19.8	2.1	5.5
Philadelphia	27	39°53'N	5.4	14.0	1.5	3.9
Pittsburgh	40	40°21'N	10.6	27.4	3.0	7 7
Reading	33	40°23'N	7.6	19.8	2.2	5.6
Scranton	32	41°24'N	7.2	18.8	2.1	5.4
Williamsport	20	41°15'N	3.3	8.4	0.9	2.4
RHODE ISLAND						
Block Island	17	41°10'N	2.5	6.4	0.7	1.8
Providence	21	41°44'N	3.5	9.2	1.0	2.7
SOUTH CAROLINA						
Charleston	56	32°54'N	18.7	48.6	4 13	10.7
Columbia	47	33°57'N	13.9	36.0	3.2	8.2
Florence	56	34''11'N	18.7	48.6	4.3	11 1
Greenville	52	34''51'N	16.5	42.8	3.9	10.0
Spartanburg	49	34°58'N	14 9	38.7	3.5	9 1
SOUTH DAKOTA						
Huron	38	44°23'N	9 7	25.1	3.1	8.0
Rapid City	41	44°09'N	11.0	28.6	3.5	9.0
TENNESSEE						
Bristol	53	36°29'N	17 1	44.2	4.2	11.0
Chattanooga	58	35°02'N	19 9	51 5	4.7	12.2
Knoxville	48	35°49'N	14 4	37.4	3.5	9.0
Memphis	51	35°03'N	16 0	41 4	3.9	10.0
Nashville	52	36°07'N	16.5	42.8	4 1	10.5
TEXAS						
Abilene	38	32°26'N	9 7	25 1	2 1	5.4
Amarillo	38	35°14'N	9 7	25 1	2 3	5.9
Austin	42	30°18'N	11 5	29.8	2.3	6.0
Brownsville	28	25°55'N	5.8	14 9	1.0	2.6
Corpus Ghristi	33	27°46'N	7 6	19 a	1.4	3 7
Dallas	51	32°51'N	16 0	41 4	3.6	9.2
Del Rio	27	29°20'N	5.4	14 0	1.0	2 7
El Paso	28	31°48'N	5.8	14 9	1 2	3.2
Fort worth	46	32°49'N	13.4	34 a	3.0	7 7
Galveston	49	29°16'N	14.9	38.7	2.9	7 5
Houston	57	29°39'N	19 3	50.0	3.8	9 9
Laredo	36	27°32'N	8.8	22 9	1.6	4.2
Lubbock	52	33°36'N	16 5	42 a	3.7	9 7
Palestine	46	31°45'N	13 4	34 a	1.6	4.2
Port Arthur	72	29°58'N	28 7	74 4	5.8	14 9
San Angelo	45	31°22'N	12 9	33.5	2 7	7 0
San Antonio	37	29°32'N	9.3	24 0	1.8	4 7
Victoria	49	28°47'N	14 9	38.7	2 9	7 4
Waco	35	31°37'N	8 4	21.a	1.a	4.6
Wichita Falls	52	33°59'N	16.5	42.8	3.8	9.8

TABLE 1g

City	Isokeraunic Level	Latitude	Total Flashes per Year per kM²	Total Flashes per Year per mi²	Flashes to Ground per Year per kM²	Flashes to Ground per Year per mi²
UTAH						
Milford	28	38°24′N	5.8	17 9	1.5	3.9
Salt Lake City	35	40°46′N	8.4	21.8	2 4	6.2
VERMONT						
Burlington	28	44°28′N	5.8	14.9	1.9	4.8
VIRGINIA						
Cape Henry	39	36°56′N	10.1	26.3	2.5	6.6
Lynchburg	35	37°20′N	8.4	21.8	2.2	5.6
Norfolk	38	36°53′N	9.7	25.1	2.4	6.3
Petersburg	41	37°14′N	11.0	28 6	2.8	7 3
Richmond	40	37°30′N	10.6	27 4	2 7	7.0
Roanoke	42	37°19′N	11 5	29.8	2.9	7.6
WASHINGTON						
Ellensburg	11	47°02′N	1.2	3.1	0.4	1 1
Olympia	3	47°00′N	0.1	0 3	0.04	0 1
Port Angeles	4	48°08′N	0 2	0 5	0 1	0.2
Seattle	5	47°31′N	0.3	0.8	0 1	0.3
Spokane	11	47°33′N	1.2	3 1	0 4	1 1
Stampede Pass	8	47°17′N	0 7	1 8	0 2	0 6
Stevenson	10	45°40′N	1.0	2.6	0.3	0.9
Tacoma	6	47°09′N	0.4	1 1	0 2	0 4
Tatoosh Island	3	48°23′N	0 1	0.3	0 03	0.1
Walla Walla	9	46°06′N	0.8	2 2	0.3	0 7
Yakima	5	46°34′N	0 3	0 8	0 1	0 3
WEST VIRGINIA						
Charleston	47	38°22′N	13 9	36.0	3 7	9 5
Elkins	46	38°53′N	13 4	34 8	3.6	9 3
Parkersburg	43	39°21′N	12.0	31.0	3 2	8.4
WISCONSIN						
Green Bay	32	44°29′N	7 2	18 8	2 3	6.0
La Crosse	36	42°47′N	8 8	22 9	2 7	7.0
Madison	41	43°08′N	11 0	28.6	3.4	8.8
Milwaukee	33	42°57′N	7.6	19.8	2 3	6.0
WYOMING						
Casper	39	42°54′N	10 1	26 3	3 1	8 0
Cheyenne	46	41°09′N	13 4	34 a	3.9	10.0
Lander	22	42°48′N	3.8	10.0	1 2	3 0
Rock Springs	40	41°36′N	10.6	27 4	3 1	8 0
Sheridan	35	44°46′N	8.4	21.8	2 7	6 9

arresters as light, medium, heavy or maximum duty, dependent on device capability when exposed to impulse discharge current and AC discharge current (Table 2). Correlation of specification requirements with expected lightning effects would be helpful in selection of devices.

TABLE 2

CLASSIFICATION CRITERIA
(REA PE-80)

Test/Paragraph	Light	Medium	Heavy	Maximum
Max. Single Impulse Discharge, Par. 4.3.1	5kA	5kA	10kA	20kA
Impulse Life, Par. 4.3.2 (Number of Surges)	10	100	400	1000
AC Discharge Current, Par. 4.3.3	10A	20A	65A	200A

Real time lightning data does not appear to be beneficial to communications as partial shutdowns to avoid damage may be impractical. The lightning effects have already been considered in the network design, including microwave and radio transmissions.

LIGHTNING HAZARDS OVERVIEW —AVIATION REQUIREMENTS AND INTERESTS—

Major Philip B. Corn
Air Force Flight Dynamics Laboratory

I am glad to have this opportunity to talk with you today about aviation requirements and needs associated with lightning hazards to aircraft. I will present a brief overview focussing on the problems posed by lightning to current aircraft; the hazard it constitutes to the advancing generation of new technology aircraft, with emphasis on electrical and electronic subsystems; and finally the research and technology requirements imposed by this hazard. To illustrate these requirements I will briefly sketch our laboratory lightning protection program.

By way of further introduction, I want to mention that since 1975 the Air Force Flight Dynamics Laboratory (AFFDL/FES) has been the Air Force's focal point laboratory for research into lightning and static electricity protection for aircraft. We work closely with the Aeronautical Systems Division, the corresponding focal point for atmospheric electricity hazards protection (AEHP) engineering development. We also maintain contact with the Air Force Inspection and Safety Center; with Air Weather Service, the USAF outlet for operational meteorological services; and with the Air Force Geophysics Laboratory (formerly AFCRL). Moreover, in recent years we have found that many of our specific concerns and AEHP research goals correspond closely with those of USN, NASA, FAA and NOAA, as evidenced by the increasingly joint nature of implementing research efforts. Because lightning hazards in many ways do not respect the distinctions between military, air carrier, and general aviation activities, I will largely call upon Air Force experience for this overview, although the agenda suggests specifically "commercial" aviation concerns.

The first two tables list some of the characteristics of lightning relevant to interactions with aircraft and give corresponding incident histories. The cost has clearly been significant. Earlier speakers have described the very high currents, potentials and energies experienced in a lightning flash. When an aircraft intercepts such a direct lightning strike, the high peak currents and longer continuing currents can cause distortion, burning and pitting of metal structures, penetration of thin skins, destruction of unprotected nonmetallic components such as fiberglass wingtips or radomes, and possible conduction of damaging, high currents into the aircraft interior. Penetration of fuel tank skins or sparking of components inside fuel tanks may cause ignition, if a favorable fuel/air mixture is present, with disastrous results {ref 12). Various means of protection against these "direct effects"

TABLE 1

AIRCRAFT LIGHTNING STRIKE CHARACTERISTICS AND COST

- Worldwide phenomenon - 1 flash every 20 seconds on average in a storm, 1800 storms simultaneously worldwide; activity varies with climate, season, hour, location, altitude. Turbulence generally correlated with lightning activity.

- Aircraft penetration through high electric field region may trigger lightning strike. Two or more attachment points for each strike.

- Commercial airline data - about one direct strike per aircraft annually, many nearby strikes.

- Air Force data - fewer strikes shown than commercial due to mission profiles, avoidance, reporting procedures. Much greater strike frequency in European Theater due to greater activity and route constraints. Strikes may be sustained even if active storm areas are avoided.

  - more than 50 percent of USAF weather-related aircraft mishaps are caused by lightning strikes.

  - dollar loss incurred in lightning-associated mishaps in the last five years exceeds 21 million dollars.

TABLE 2

TEN YEAR HISTORY OF USAF LIGHTNING INCIDENTS

A/C	STRUCTURE	ELECTRICAL, INSTRUMENTS	FUEL	OTHERS	CATASTROPHIC	MAJOR	MINOR
F101	1	4		1	1	2	3
F102				3			3
F106	3	5			1	2	5
F-111*	3	15		6	1*	1	22
F-4	14	26	4	6	2	1	47
F-15	1	1					2
T-29	3	2		1			6
T-38	2	1					3
C119		1			1		
C124	1						1
C130**	4	6	1**	1	1**		11
C131	3	2					5
KC135	8	5	1		1		13
C141	3	3					6
OTHER	7	5					12
B-52	12	2		1		1	14
HH-43	1				1		
TOTALS	66	78	6	19		7	153

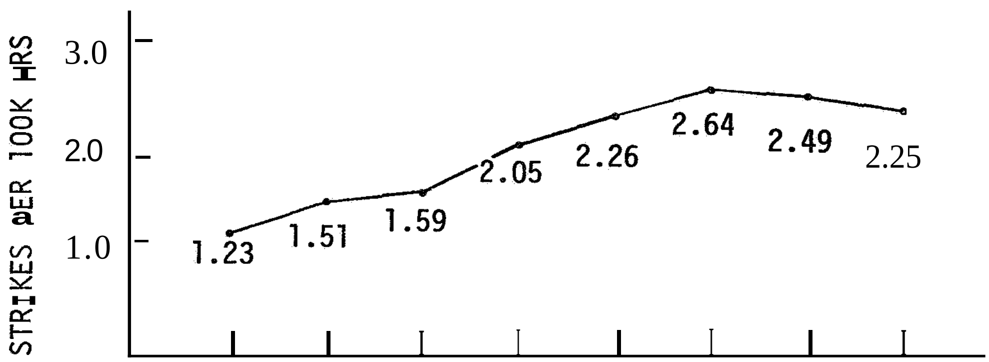
*F-111F lost 29 March 78 near RAF Lakenheath, UK with two crew fatalities. Lightning effects on electrical and electronic control subsystems were a factor.

**C-130E lost 30 Nov 78 near Charleston, SC with 6 fatalities. Lightning burn-through of wing skin by attached stroke caused fuel tank explosion.

have been devised (ref 5, 6) and applied, generally rather systematically, for military and air carrier aircraft in whose design organizations an adequate lightning protection technical base usually exists. This is not true for general aviation aircraft. Although lightning had not previously been considered a problem for these aircraft, they are now experiencing increasing lightning strike rates as expanding utilization modes bring them into more frequent operation under instrument conditions. Such an increasing trend is also indicated by the USAF strike rates shown in Figure 1.

FIGURE 1

USAF LIGHTNING STRIKE RATES, 1969-1976
(THREE YEAR RUNNING AVERAGE)



In addition to the direct, or physical effects previously described, there are "indirect effects," such as voltages induced inside aircraft components and subsystems by the rapidly changing skin currents and associated fields, which are less well understood. These indirect effects may generate electrical transients of hundreds or thousands of volts' magnitude, and can constitute a potentially serious threat to aircraft electrical or electronic systems. It has recently been found in a NASA/AFFDL/SRI airborne measurement program that significant induced effects can also be produced by <u>nearby</u> lightning discharges, a much more frequent occurrence than direct strikes to aircraft (ref 4, 11).

A full spectrum of lightning hazards is listed in Table 3, with causes and associated criticality. Virtually any of these hazards is potentially capable of causing aircraft loss or loss of life under foreseeable conditions, and probably has.

Fully half of these hazards relate to effects on electrical or electronic systems. It should also be observed that a critical, multiple redundant electrical control system otherwise protected against random, single channel failure, may be susceptible to interruption due

TABLE 3

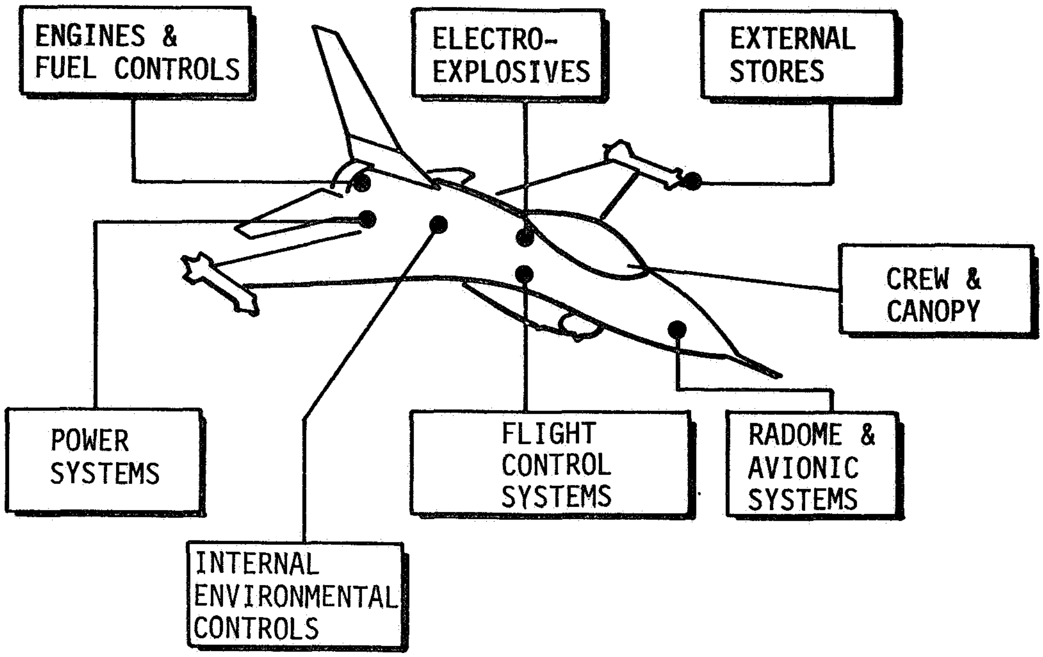
ATMOSPHERIC ELECTRICITY THREATS TO AIRCRAFT

HAZARD	CAUSE	HAZARD CRITICALITY
MALFUNCTION/FAILURE OF ELECTRONIC CONTROL SYSTEMS	LOW TOLERANCE TO ELECTRICAL TRANSIENTS CAUSED BY DIRECT/INDUCED LIGHTNING OR STATIC ELECTRIFICATION EFFECTS. MAY SIMULTANEOUSLY AFFECT PARALLEL 'REDUNDANT' SYSTEM.	MINOR TO CATASTROPHIC
FUEL TANK FIRE OR EXPLOSION	FUEL VAPOR IGNITION CAUSED BY STATIC ELECTRICITY OR LIGHTNING EFFECTS.	MINOR TO CATASTROPHIC
LOSS OF ENGINE POWER	POSSIBLE LIGHTNING ACOUSTIC SHOCK AT ENGINE INLET, OR ELECTRICAL TRANSIENT EFFECTS ON ENGINE CONTROLS.	MINOR TO CATASTROPHIC
INADVERTENT RELEASE/IGNITION OF EXTERNAL STORES	PREMATURE ACTIVATION CAUSED BY LIGHTNING OR STATIC ELECTRIFICATION EFFECTS.	SERIOUS TO CATASTROPHIC
RADOME, CANOPY, AND WIND-SHIELD DAMAGE	DIRECT LIGHTNING STRIKES; ARC DISCHARGE CAUSED BY STATIC ELECTRICITY BUILDUP.	MINOR TO SERIOUS
INSTRUMENTATION PROBLEMS/ COMMUNICATIONS, NAVIGATION & LANDING SYSTEM INTERFERENCE	TRANSIENT EFFECTS CAUSED BY STATIC ELECTRICITY BUILDUP & DIRECT AND NEARBY LIGHTNING STRIKES.	MINOR TO CATASTROPHIC
STRUCTURAL DAMAGE	DIRECT LIGHTNING ATTACHMENT TO AIRCRAFT.	MINOR TO SERIOUS
PHYSIOLOGICAL EFFECTS ON CREW	FLASH BLINDNESS & DISTRACTING OR DISABLING ELECTRICAL SHOCK CAUSED BY DIRECT & NEARBY LIGHTNING STRIKES	MINOR TO CATASTROPHIC

to simultaneous defeat of all channels by high level transients induced by lightning strike. Another point of interest is the possible effect of lightning-generated acoustic shock. Apparently the major portion of lightning energy is transmitted through this mechanism.

FIGURE 2

SYSTEMS SUSCEPTIBLE
TO ATMOSPHERIC ELECTRICITY HAZARDS



The large number of potentially susceptible subsystems employed on a modern aircraft are illustrated in Figure 2. Although the example shown is a military airframe, and in fact one of the more exhaustively tested aircraft, the majority of these subsystems may be found on modern general aviation and air transport aircraft. Indeed, most of these subsystems are planned for upgrade within the next five years by means of sophisticated microelectronic replacements with improved capabilities and greater inherent sensitivity to electrical transients.

A common theme in this review of hazards and susceptible systems has been the need for protection of microelectronic circuitry and subsystems. These advanced technology devices offer very great promise of expanded control flexibility and improved systems performance, safety and efficiency. However, the low operating voltages and power handling capabilities of integrated circuitry, particularly large scale integrated (LSI) circuits, also make them inherently susceptible to induced transients.

In the same way, the introduction of advanced aircraft structures and materials with their very different and unfamiliar electrical and radiation shielding properties requires considerable care to ensure enclosed subsystems are fully protected. On the other hand, excessive protection measures can impose severe cost and weight penalties, cancelling the intended benefit from these new technologies. The requirement is clearly for design criteria and guides for optimum protection of these systems in advanced airframes and structures. Present MIL-SPECs and standards are inadequate.

TABLE 4

TECHNICAL NEEDS - NASA/FAA/NOAA WORKSHOP, 28-30 MAR 78
SUMMARY REPORT OF LIGHTNING/STATIC ELECTRICITY COMMITTEE

1. IN-FLIGHT DATA ON LIGHTNING ELECTRICAL PARAMETERS
2. TECH BASE AND GUIDELINES FOR PROTECTION OF ADVANCED SYSTEMS AND STRUCTURES
3. IMPROVED LABORATORY TEST TECHNIQUES
4. ANALYSIS TECHNIQUES FOR PREDICTING INDUCED EFFECTS
5. LIGHTNING STRIKE INCIDENT DATA FROM GENERAL AVIATION
6. LIGHTNING DETECTION SYSTEMS
7. OBTAIN PILOT REPORTS OF LIGHTNING STRIKES
8. BETTER TRAINING IN LIGHTNING AWARENESS

A comprehensive view of lightning protection technical needs, both engineering and operational, is given in Table 4, showing needs in descending order of relative priority. This listing summarizes conclusions reached by a study committee with USAF/USN/NASA/industry representation, which took part in the 1978 workshop on aviation environmental data needs sponsored by NASA, FAA and NOAA (ref 9). Several of these needs will be examined more closely. Perhaps the most significant finding for purposes of this workshop is the high priority assigned to in-flight measurement of lightning electrical parameters. In-flight measurements are needed to accurately define the threat to aircraft microelectronic subsystems, serving as necessary inputs for analytic model techniques, ground simulation tests and detailed exposure estimates (ref 7). For both nearby and attached strikes, required data include measurements of ambient electromagnetic fields, skin currents, induced electrical transients in circuitry, and fields within the aircraft. High resolution measurements of waveforms with a wide enough data base to derive meaningful threat statistics are required. Confirming ground measurements are also highly desirable, although it may be possible to obtain this confirmation by means of satellite lightning data.

The second priority listed in Table 4 identifies the need to produce protection guidelines. This will require a major program including demonstration testing, evaluation, trade-off and integration of various possible complementary techniques for hardening of components, shielding of subsystems, routing, filtering, limiting, use of fiber optics, and similar strategies. These must be evaluated in concert with existing electrumagnetic compatibility (EMC) and nuclear electromnagnetic pulse (MEMP) protection techniques and requirements. The third and fourth needs listed support this protection guideline requirement, as will data obtained from the in-flight measurement program. Additionally, lightning detection/avoidance systems may play an important part in helping to reduce exposure to lightning. A similar lightning avoidance function can potentially be performed by near real time satellite lightning data.

Figure 3 outlines the lightning protection program undertaken and planned by AFFDL, with participation in several cases by other agencies. In large part this program corresponds to the first four entries in Table 4, and suggests their close interrelationship. A major effort since 1975 has been experimental test development, which has pursued the direction set by the Lightning Transient Analysis (LTA) test several years ago. A laboratory in-house and contracted effort over several years' time, employing an original developer of the technique, has refined and extended this procedure for measuring aircraft susceptibility to impulse-induced electrical transients, and placed it on an improved theoretical and practical base. The analytic efforts, which are aimed at developing the ability to predict transients on aircraft circuitry from aircraft skin current distributions, and ultimately from more general specifications, have taken several different approaches. In the first, a model for the lightning interaction was developed from first principles. In the second approach, an existing model developed by the Air Force Weapons Laboratory for the nuclear electromagnetic pulse (NEMP) problem, a related interaction, was modified for lightning use. Another approach, undertaken by Naval Air Systems Command, has used a version of the Intrasystem Electromagnetic Compatibility Analysis Program (IEMCAP), a large scale EMC model. At least several of these appear promising, but none has as yet been fully validated. An in-flight measurement program is being negotiated with NOAA's National Hurricane and Experimental Meteorology Laboratory (NHEML) on a hurricane research aircraft and is expected to begin this summer. Finally an Advance Development Technology Program is planned, a large scale, cooperative interagency protection demonstration effort, leading to the required protection guidelines and standards.

In ending this overview with an outline of the AFFDL program, I wish to make clear my belief that the common aviation lightning protection goals described will only be achieved be a well-coordinated joint effort on the part of a number of individuals and agencies. The availability of appropriate lightning data from space platforms may well advance important aviation engineering and operational goals in such a joint effort.

ATMOSPHERIC ELECTRICITY HAZARDS PROTECTION (AEHP) PROGRAM

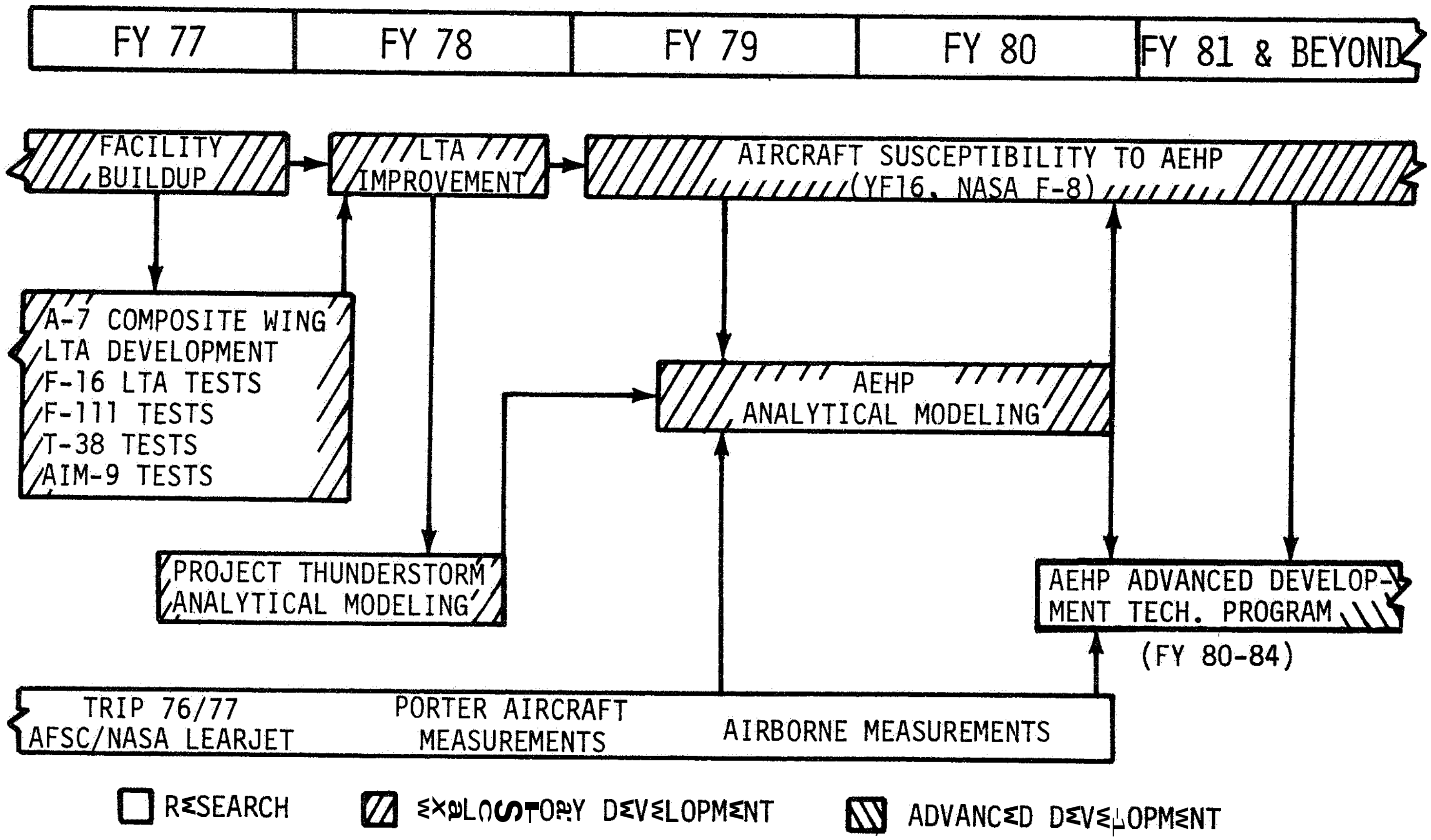


FIGURE 3

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THE ATMOSPHERIC ELECTRIC GLOBAL CIRCUIT

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SUMMARY

(1) The global circuit describes the atmospheric electric current-flow in the earth atmosphere between ground and the ionosphere.

(2) The generator in this circuit is represented by the world thunderstorm activity.

(3) The thunderstorm generator hypothesis is based on a close correlation between the magnitude and the diurnal variation of the supply current (thunderstorm generator current) and the load current (fair weather air-earth current density integrated over the earth surface).

(4) The diurnal variation of the world wide thunderstorm activity is obtained from a combination of the local diurnal variation of thunderstorm occurrence at Kew, England, with the world thunderstorm day statistic of Brooks.

(5) The current output of the single storm has been obtained from field and conductivity measurement made from balloons flying over thunderstorms. This value is then multiplied with the number of thunderstorms active simultaneously on the earth obtained from Brooks statistic.

(6) The diurnal variation of the load current is assumed to be proportional to the diurnal variation of the fair weather field over the oceans recorded during the ocean cruises of the Carnegie Institution. Field records of continental stations show a pronounced diurnal variation according to local, not to world time. It has been assumed that these local time variations cancel by integration over the globe.

(7) The magnitude of the load current is calculated by multiplying the average air-earth current density with the surface of the earth.

(8) Each one of these experimental results and the conclusions drawn thereof is open to severe criticism. The only exception is the diurnal variation of the oceanic field.

(9) Worldwide lightning survey from satellites would remove the large uncertainty in the determination of the world thunderstorm activity used in point (4).

(10) Measurements of thunderstorm currents injected into the ionosphere from a tethered satellite would provide an excellent check on the current output of the individual storm [point (5)].

(11) If cloud discharges can be differentiated from ground discharges in the records of an optical lightning satellite and if it can be proven that ground discharges carry the main part of the charge transfer from the storm base to ground, the request of point (10) could be obtained from the data of the optical lightning satellite.

(12) It can be expected that data provided by lightning survey satellites will furnish a base to accept or reject the thunderstorm generator hypothesis, which is one of the fundamental problems in atmospheric electric research.

The thunderstorms--two are shown in Figure 1--summed over the world represent the electric generator in this circuit. This generator drives a current, from its positive pole located in the top of the storms, towards the ionosphere, where it spreads out horizontally, flows in the fair weather areas down towards the earth, returns in the earth crust to the areas underneath the storms, and then flows vertically upwards to storm base and to the negative pole of the generator located in the lower part of the storm. This current flow is indicated in Figure 1 by arrows. It is interesting to review briefly the chain of events that lead to this model.

At the beginning of our century it was realized that the atmospheric electric fair weather field was a worldwide phenomenon. Since at this time the electrostatic way of thinking prevailed, the permanent existence of the fair weather field was explained by a negative charge on the surface of the earth. The air was assumed to be an excellent insulator, therefore the earth, once charged, would keep this charge and produce the fair weather field indefinitely. One cubic meter air has a resistance of $5 \cdot 10^{13}$ Ohm which for all practical purposes is indeed an excellent insulator. Still it is not good enough to keep a charge on the earth surface for an indefinite long time. After the slight conductivity was detected it was easy to calculate that the earth would loose its charge in about one hour. The logical conclusion was that a generator exists to continuously replenish the charge lost by the air conductivity. The search for this generator has fully occupied the atmospheric electric scientists in the first quarter of our century. We may face the same situation again if it turns out that the solution offered--namely that the worldwide thunderstorm activity provides the generator--cannot stand up to the mounting critical reevaluation of the data on which this solution is based. The lightning and thunderstorm survey from satellites could furnish the information needed to accept or reject the thunderstorm generator hypothesis.

From Fischer and Mühleisen, 1968

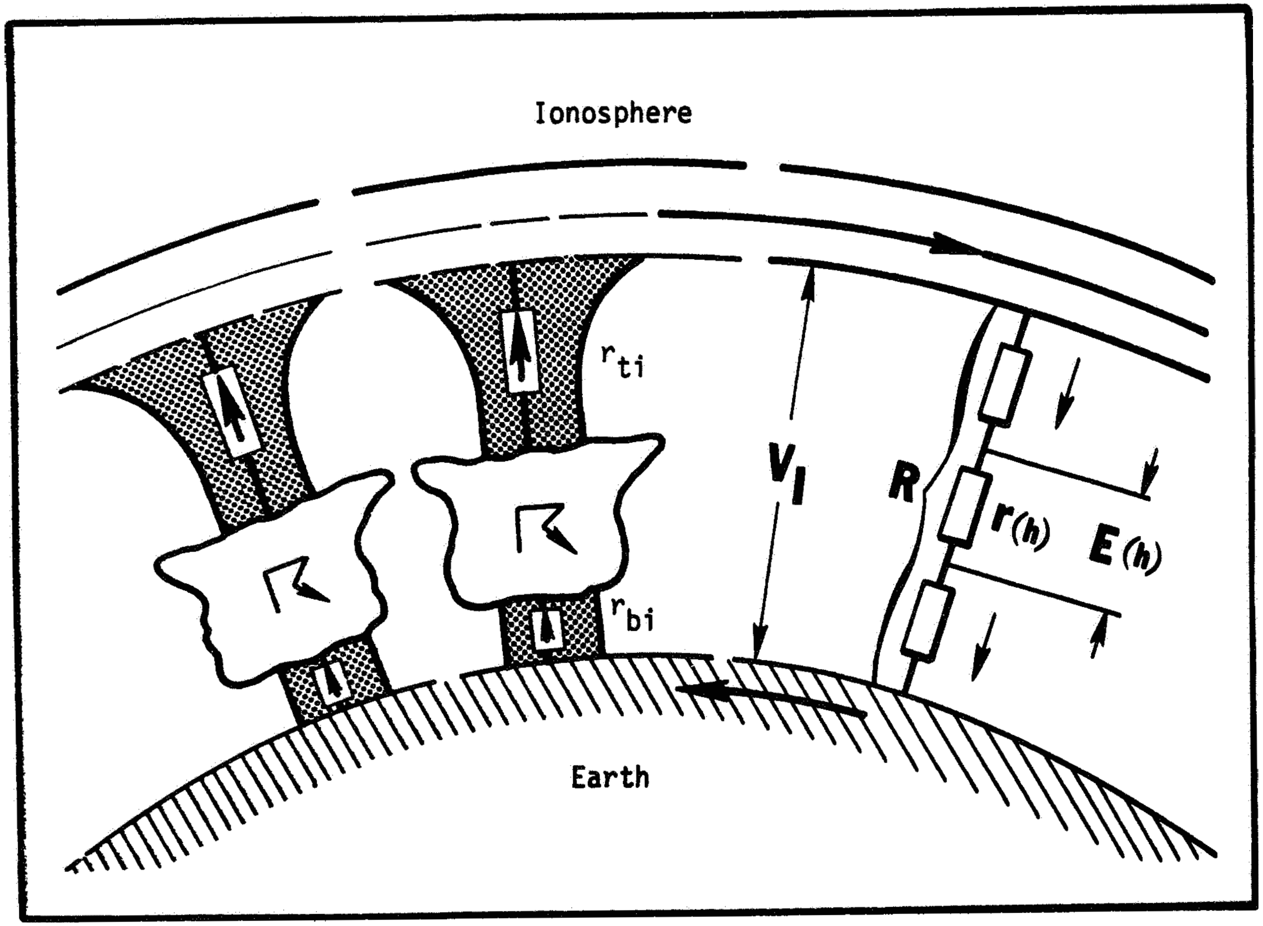

FIGURE 1. MODEL OF THE GLOBAL CIRCUIT AS A LEAKY SPHERICAL CONDENSOR.

Schweidler (1932) published a review of all the different processes of known and newly invented physical phenomena that have been suggested to explain the maintenance of the charge of the earth. The most convincing hypothesis offered was the thunderstorm generator favored by C. T. R. Wilson, A. Wigand and other scientists of this time. Whipple and Scrase (1936) added substantial weight to the thunderstorm hypothesis by the following arguments. If the thunderstorm hypothesis is correct the load current I_L should be equal to the supply current I_S of the thunderstorm generator and both of these currents should have the same diurnal variation. Hereby it is implicitly assumed that the resistors in the circuit do not change.

The resistors in the circuit are represented by the electrical resistance r_{ti} of the column of air from the top of the storm to the ionosphere and the resistance r_{bi} from the ground to the base of the storm. The index i indicates that this is the resistor of an individual storm. All the r_{ti} and r_{bi} are connected in parallel and can be lumped together in one representative resistor R_t and R_b.

$$1/R_t = \sum_i^N 1/r_{ti} \qquad 1/R_b = \sum_i^N 1/r_{bi} \tag{1}$$

In series with these resistors is the resistor R (see Figure 1) of the air between the ionosphere and ground in the fair weather regions of the globe. The load resistor R_L of the circuit is then given by

$$R_L = R_t + R + R_b \tag{2}$$

The current I_L flowing through resistor R_L is the load current. The value of I_L may be obtained by integrating the air-earth current density i over the surface S of the earth. The average air-earth current density is assumed to be

$$i = 3\ \mathrm{pA/m^2} \tag{3}$$

The surface of the earth is

$$S = 510 \cdot 10^{12}\ \mathrm{m^2} \tag{4}$$

and the load current follows from Equations 3 and 4

$$I_L = i \cdot S = 1530\ \mathrm{A} \tag{5}$$

According to Equation 5 the diurnal variation of the air-earth current density i and of the load current I_L should be the same since the earth surface is a constant. It was one of the major achievements in atmospheric electricity that a worldwide diurnal variation of the electric field on the oceans according to universal time was found by Parkinson and Torreson (1930, 1931) and by Sverdrup (1927) (Figure 2).

Since the diurnal change of the conductivity λ on the oceans is negligible and field E, conductivity λ, and air-earth current density i are linked by Ohm's law

$$i = XE \tag{6}$$

the diurnal variation of the air-earth current density follows closely the diurnal variation of the field. On the continents, however, the field E as well as the current density i display a diurnal variation with local time, not with universal time, and therefore would not fit into a worldwide pattern. But Paramonow (1950) could show that the worldwide diurnal variation would emerge if the fields of many continental stations distributed around the globe were averaged when synchronized to universal time. This would mean that local influences would cancel on a worldwide basis.

With the load current I_L given by Equation 5 and the diurnal variation shown in Figure 2, it remains to determine the supply current I_S and its diurnal variation. For this purpose Whipple and Scrase (1936) obtained the average thunderstorm probability as a function of local time--shown in Figure 3--from corona current records at Kew, England. With the assumption that a similar diurnal thunderstorm distribution occurs on all other continents, they combined this probability curve with the world thunderstorm day statistic of C. E. P. Brooks (1925) and obtained the diurnal variation of the worldwide thunderstorm activity as a function of universal time shown in Figure 4. The smaller three curves with their maxima at 8, 14, and 20 h universal time represent the contributions of the major thunderstorm regions Asia and Australia, Africa and Europe, and America, respectively. The summation of these three curves represents, then, the diurnal variation of the world thunderstorm activity. This is the largest curve marked "The World" in Figure 4.

There is a certain similarity between the diurnal variation of the world thunderstorm activity (Figure 4) and the field or current density on the oceans (Figure 2). The minima of both curves occur at 3 h universal time and the maxima at 19 h universal time. The "World" curve has another maxima at 14 h that is even slightly higher than that at 19 h and mars somewhat the similarity. However, even more pronounced is the difference of the amplitude of the modulation of the two curves. The amplitude of the swing in the ocean field curve is only ±20% of the average value, whereas the amplitude of the modulation of the thunderstorm activity is ±47% of the average value. To reduce the amplitude of the thunderstorm modulation, Whipple and Scrase (1936) assume that

Reproduced from Dolezalek 1972

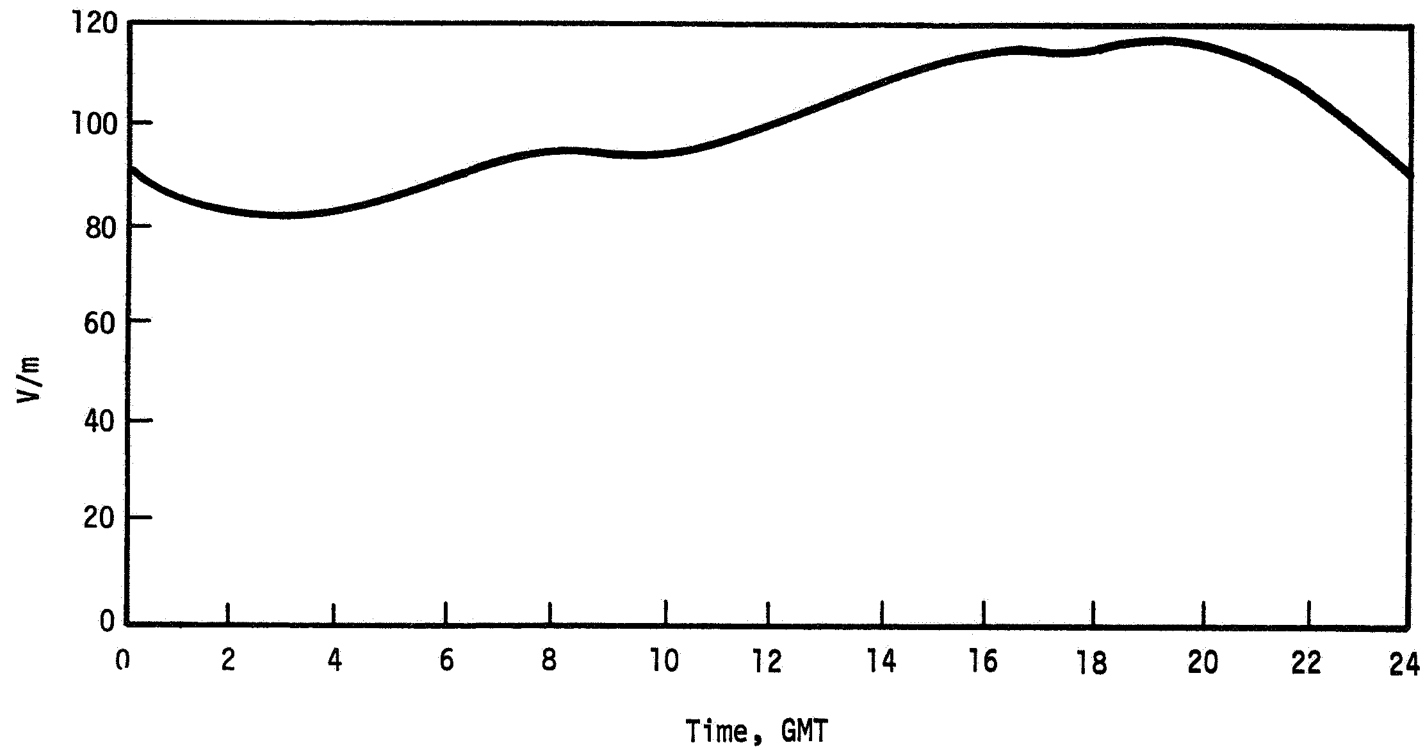

FIGURE 2 ANNUAL CURVE OF DIURNAL VARIATION OF THE ATMOSPHERIC ELECTRIC FIELD ON THE OCEANS AS MEASURED BY THE CARNEGIE. (PARKINSON AND TORRESON, 1931)

From Israël, 1961

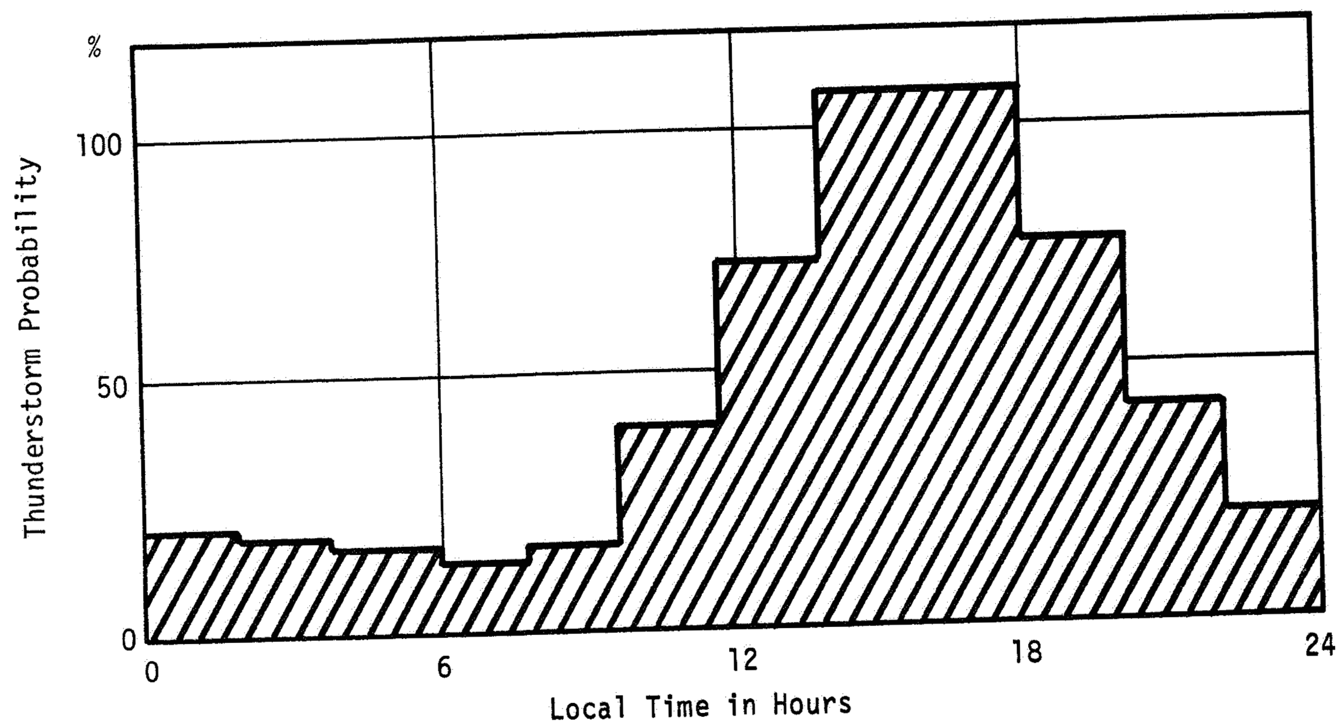

FIGURE 3

From Dolezalek, 1972

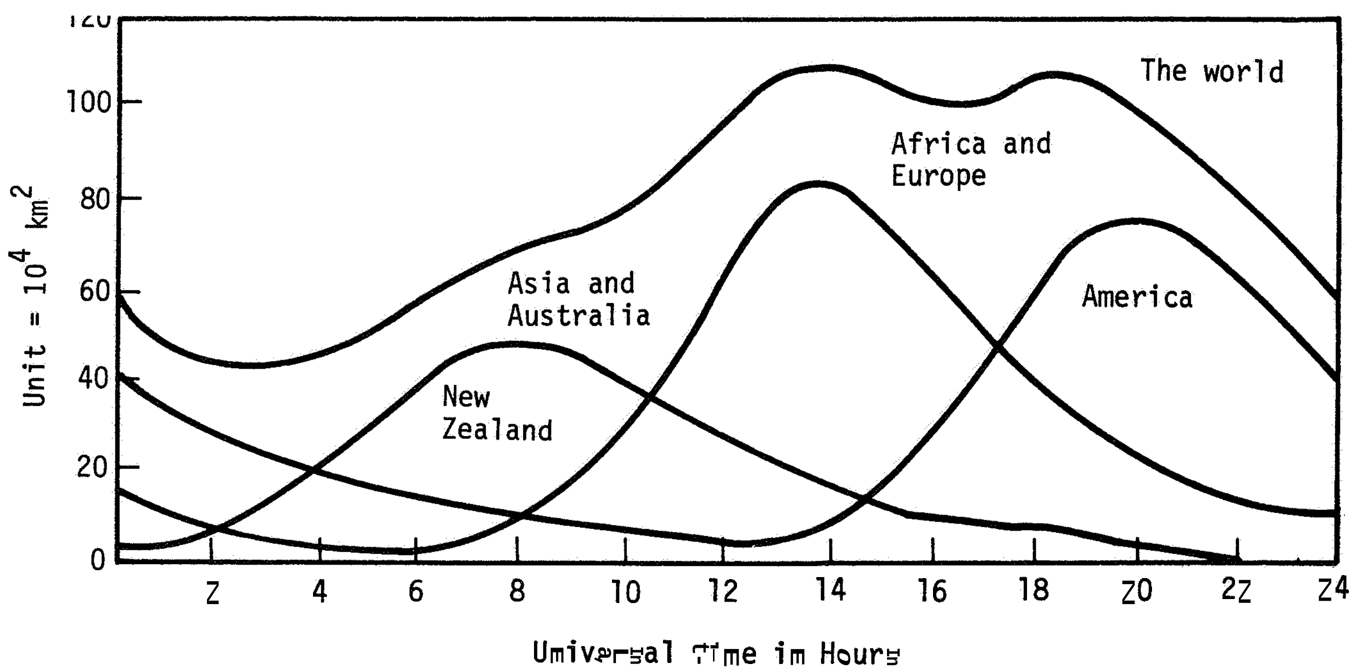

FIGURE 4. ANNUAL CURVE OF THE DIURNAL VARIATION OF GLOBAL THUNDERSTORM ACTIVITY ACCORDING TO WHIPPLE AND SCRASE (1936).

on the oceans about 1.3 as many storms occur as on the continents, and that these ocean storms do not have a diurnal variation. If an equivalent steady supply current is added to the supply current of the continental storms then modulation of the world thunderstorm activity would be similar to the ocean field modulation.

Since Brooks himself called attention to certain marked deficiencies of the thunderstorm day data, for instance that there are vast areas, especially in the Southern Hemisphere and on the oceans, with very few if any records of thunderstorm occurrence, the somewhat arbitrary assumptions of Whipple and Scrase seem at least to be possible. However, the first assumption that the ratio of ocean to continental storms is about 1.3 could not be confirmed by very recent satellite data reported by Turman and Edgar (1978) (personal communication). They found that at dawn the ratio ocean to continental storms is 0.46 and at dusk 0.14. The year around average is about 0.23. This result makes it unlikely that the oceans' storms have the desired effect of reducing the diurnal modulation of the world thunderstorm activity. Here the conclusion may be drawn that besides the thunderstorm generator another generator is active that has a very reduced diurnal variation and is one to two times as strong as the thunderstorm generator.

Another check on the thunderstorm hypothesis may be made in the following way. According to Brooks thunderstorm statistic there are about 1800 thunderstorms simultaneously active on the earth surface. From Equation 5 we know that the load current is 1530 A. This means that each thunderstorm should contribute in the average 0.85 A to the composite of storms constituting the global generator. The task is now to make an estimate of the current output of the average storm. However, this turns out to be a rather difficult problem. Between marginal storms with maybe ten lightning discharges spaced in one or two minute time intervals and large storm systems with an almost continuous lightning display we may have current outputs different by a factor of 10 or more. A large variation in the current output may be expected also from storms at the same location but in different seasons or in the same season but at different locations, for instance, the difference between tropical and middle latitude storms. The current output of ocean storms is practically unknown. These points are specifically mentioned here because it may be possible to obtain a survey of the current outputs of thunderstorms from tethered satellite data.

Table 1 lists a few of the reported data of the average current output of thunderstorms. In columns 1 - 4 we find location, average current output, measuring method, and references, respectively. All investigators used field recording instruments located either at the ground underneath the storm or mounted on airplanes or balloons flying over the top of the storm. The current density was obtained by Ohm's law, Equation 6, measuring or assuming the conductivity at the respective altitude. At the ground (row 1) the contribution of the conduction current density turned out to be negligible compared to the corona current. The net corona current has been determined from the field contour maps provided by Kennedy Space Center. These maps were

TABLE 1

AVERAGE CURRENT OUTPUT OF A THUNDERSTORM

Location	Average Current output	Measuring Method	Reference
Florida, KSC, USA	0.1 A	Ground Field Mills	Kasemir, Trip (1977)
European Territory USSR	0.1 - 0.2 A	Airplane above Thunderstorm	Imyanitov, et al. (1971)
Central USA	0.5 A	Balloon above Thunderstorm	Gish and Wait (1950)
Florida, USA	1 A	Airplane above Thunderstorm	Stergis, et al. (1957)

calculated from the field recordings of a network of 25 field mills. The corona constant connecting field and current has been obtained from field data measured at the ground and aloft at Kennedy Space Center by Standler and Winn (personal communication). Charge brought down to earth by precipitation or lightning discharges is not included in the current output listed in row 1.

The situation at the top of the storm is not so complex as on earth. We have to deal here only with the conduction current. Precipitation and corona currents are absent and the effect of lightning discharges is in first approximation an integral part of the field record. The difficult part in using field measurement from an airplane for current output determination is to design a flight pattern that will result in a fast enough scan of a representative thunderstorm area.

The current output of 0.5 A and 1 A listed in the last two rows of Table 1 are in good agreement with the required contribution of 0.85 A of the individual storm. The rather small value of the current output of 0.1 A determined from ground measurement may be explained by the neglection of the precipitation and lightning current. In the budget estimate of the different types of charge transfer to ground given by Israel (1961, Vol. 11, p. 71) the precipitation current is small and brings positive charge to the ground. This means it will rather subtract than add to the current output. Lightning discharges, at least cloud to ground discharges, bring in the majority of cases negative charge to ground. Therefore, they contribute to the output current, but according to this budget estimate the contribution is small. The main part of the output current has been attributed to the corona current.

This is in disagreement with our Florida measurements at Kennedy Space Center. Here the corona current would contribute only 12% to the required 0.85 A output current. On the other hand if we use the commonly accepted value of -30 C of charge brought down to ground by the average ground discharge it would require a ground flash only every 30 seconds to account for an average lightning current of 1 A. This is a very moderate ground flash frequency for an average thunderstorm and it is therefore quite possible that the bulk of the output current between cloud and ground is carried by lightning current. It is interesting to note that this type of charge transfer yas suggested more than 50 years ago by A. Wigand (1923) in a publication discussing the maintenance of the charge of the earth by lightning currents.

In our present situation such a possibility is rather intriguing. If it can be established that the current carried to ground by ground discharges and the current emerging from the top of the cloud and flowing upwards to the ionosphere are of the same magnitude or at least proportional to each other, then the optical lightning survey from satellites planned or already carried out would represent an excellent method to determine the electric current output of the worldwide thunderstorm generator. However, it would be imperative that the optical signal of cloud discharges can be differentiated from that of ground discharges. Cloud discharges have to be considered as a temporary short between the generator terminals and would not contribute to the current output. As an alternative, a survey of the world lightning activity could be made using electromagnetic radiation emitted from lightning discharges. Here it is already known that such a differentiation can be made.

The solution of the fundamental problem--namely that the world-wide thunderstorm activity produces the electric state of the atmosphere--was with some reservations accepted by the scientific community in the mid fifties of this century. However, it has not been possible to develop a generally accepted charge generating and separating mechanism for the thunderstorm. New processes acting as generators have been proposed by Frenkel (1949), by Kasemir (1956), and by many others. The weak parts in the concept of the global circuit and the thunderstorm generator are reexamined. Dolezalek (1972) writes in the summary of his critical review of the fundamental problem:

> "The classical picture which emerged in the 1920's, also called sometimes the spherical capacitor theory, is shown to be unproven or even disproven by measuring results available until now. . . . we indeed have a globally controlled current flow vertically through the atmosphere, but the connection to the thunderstorm activity is tenuous and, in fact, contradicted by proper interpretation of available measurements."

The importance of a survey of the world lightning activity from a satellite does not need to be emphasized. With regard to the fundamental problem of atmospheric electricity it should be possible with such a survey to settle the question if thunderstorms are the generators in the global circuit or not.

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NATIONAL SCIENCE FOUNDATION SUPPORT OF ATMOSPHERIC ELECTRICITY RESEARCH

H. Frank Eden

National Science Foundation

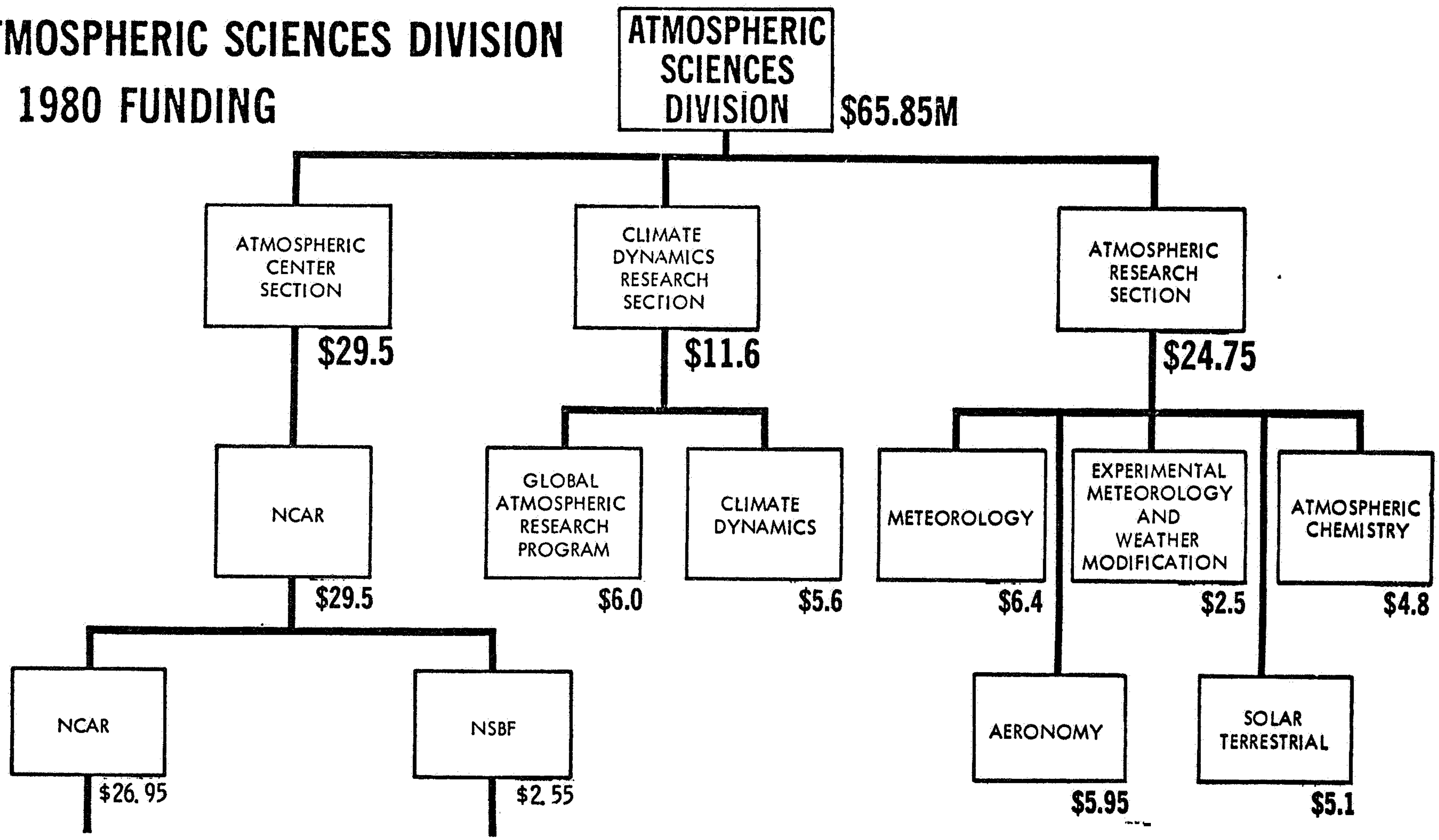
The National Science Foundation funds a broad spectrum of meteorological research through the Division of Atmospheric Sciences. Within this Division are the GARP programs, which support research appropriate to the aims of the global research program; the meteorology and experimental meteorology programs, which provide support for projects in meteorology ranging from basic fluid mechanics to observational field programs aimed at behaviour of severe storms; and the Project Office for the National Center for Atmospheric Research (NCAR). NCAR, situated in Boulder, Colorado, providing facilities required for meteorological research and supporting programs of in-house research or in cooperation with university groups. The breakdown of the division with the approximate FY 80 funding levels for the individual programs is illustrated in Figure 1.

Support for research in atmospheric electricity for the past decade has been provided through the meteorology program. In general, this support has been for research aimed at understanding the behaviour of thunderstorms and the lightning process. In the past few years, this has concentrated in the TRIP Experiment, a cooperative observational experiment whose field program has been centered for the past three years at the Kennedy Space Center. Funding for such research has been typically of the order of 7% of the budget of the meteorology program ranging, for example, from some eight grants in FY 77 for a total of $607 k to seven grants in FY 78 for a total of approximately $500,000. This coming summer, the majority of these observational programs will be carried out at the New Mexico Institute of Mining and Technology, Irving Langmuir Laboratory for Atmospheric Research in Socorro, New Mexico. The National Science Foundation contributed to the early development of this observatory.

Recently, there has been a reemergence of interest in the fair weather field of the global aspects of atmospheric electricity. Some evidence of this is in the increasing interest of researchers who are generally concerned with the behaviour of the upper atmosphere in the fair weather field. Recently, Dr. R. Roble of NCAR, together with Dr. P. Hays of the University of Michigan, published a very interesting theoretical paper on the global fair weather field investigating the effects of mountain ranges. In another project involving theory, the Foundation supported the pioneering work of Dr. T. Chiu of the South Dakota School of Mines in modelling the development and growth of electric field in thunderclouds.

The Foundation is interested in promoting work on atmospheric electricity whether in the thunderstorm area or on the topic of global electrification and fair weather field.

ATMOSPHERIC SCIENCES DIVISION
FY 1980 FUNDING



NAVY SUPPORTED RESEARCH IN ATMOSPHERIC ELECTRICITY

James Hughes
Office of Naval Research

The program of research in atmospheric electricity in the Office of Naval Research has a long history. Beginnings of the program were in the early work of the then Cornel1 Aeronautical Laboratory attempting to bring an aircraft to a zero difference of potential against the atmosphere in an attempt to solve certain problems of communication interference. Probably the more basic research program in atmospheric electricity in ONR began with the efforts of Vonnegut and Moore to validate a presumed external charging mechanism for the thunderstorm. Their efforts to prove their assumptions aroused a controversy on the mechanism of charge separation in a thunderstorm that has no8 yet subsided. The controversy acted as a valuable stimulus to the whole field of research in atmospheric electricity. One of the next major efforts of ONR in this area of research was to support Salanave's reapplication of an astronomer's technique of slitless spectroscopy to the lightning flash. Salanave's experimental work caught the interest of Uman who happened to be on the same campus, and the combination of their efforts and the efforts of the graduate students they attracted initiated a resurgence of interest in lightning physics and created a wealth of new information on the lightning process which we are today exploiting for numerous applications.

In the current program, one of our major support efforts in Atmospheric Electricity (AE) is at the New Mexico Institute of Mining and Technology (NMIM&T). This work consists of a mountain top field program at the Langmuir Observatory as well as theoretical and laboratory work. A principal goal of the program is to understand the interplay of cloud electrification, lightning location and geometry, and the precipitation process. The special tools of the research are a fast scan radar (20 seconds/full sky scan) based on application of wide band noise; especially developed balloon probes for measurement of cloud electric fields; acoustic arrays for deriving lightning location and geometry; an especially equipped powered sail plane for in-cloud and cloud vicinity measurements; plus a host of other radar, photographic, and atmospheric electrical measurement equipment. In addition, there is an extensive rain gauge network and equipment for the standard atmospheric measurements. The principal investigators in this AE field program at the NMIM&T are M. Brook, C. B. Moore, W. Winn, H. Christianson, C. Holmes and P. Krehbiel.

A frequent collaborator in the NMIM&T program is A. Few of Rice University, who is supported by ONR for the development and application of special balloon probes for electric field measurements in and around clouds. J. Latham of the University of Manchester is another ONR contractor who participates in the program. Latham's work is to make measurements of drop size and the related charge. The group from Commonwealth Scientific and Industrial Research Organization (CSIRO) has partial ONR support for in- and above-cloud observations.

The Langmuir Observatory is host during the thunderstorm season of 1979 (and probably 1980 and 1981) to the Thunderstorm Research International Program (TRIP). Various other ONR investigators participate in this program, among whom are B. Vonnegut and his associates from the State University of New York at Albany. One of Vonnegut's interests is the measurement of electric fields at sea and the differences of the electric regime at sea from that over land. A close collaborator (and student) of Vonnegut in the ONR program is R. Toland of the U.S. Army Military Academy.

Laboratory work at the NMIM&T includes extended research on the charge separation process across a moving ice boundary as in a hydrometeor containing mixed phases of ice and water. Other electrical properties of ice are also included in this research. G. Gross is the principal investigator.

G. Freier at the University of Minnesota at Minneapolis does experimental laboratory work, under ONR support, on the phenomenology of lightning by means of high voltage sources and various geometries of electrodes. In his recent investigations, he has been looking at the role of the junction process of lightning in possibly suppressing competing strokes. Freier's theoretical work in AE includes attempts to explain the morphology of the electric field of the earth in terms of the magnetic field of the earth and also the structure of ball lightning. He also has made for several years systematic measurements of the thunderstorm regime around Minneapolis which he has used recently for a solar-terrestrial study.

Nearby at the University of Minnesota at Duluth, D. Olson has evolved a collaborative network of instrumentation around the auroral oval for electric field and current measurements with which he is searching for evidence of solar-terrestrial effects. He also has assisted the Navy with measurements at naval installations of electric field intensification due to dust storms.

M. Uman at the University of Florida at Gainesville conducts, under ONR support, a program of lightning research in which he attempts to derive lightning current values from field measurements of electric and magnetic fields, range to stroke, and stroke rise time. This work has furnished the beginnings of a climatology of lightning current distributions. Collaborating with Uman in this work, and also under ONR support, is P. Krider at the University of Arizona. Krider is responsible for the sensitive equipment for measurement of the rise times of lightning currents. He has time-resolved lightning rise times to peak current down to fractions of a microsecond. Krider is also responsible for the development of advanced techniques for detecting and locating lightning strokes.

R. Hill in our program has used measurements and observations of other investigators to make detailed estimates of the energy dissipation in a lightning stroke. Using observation on a six million volt spark made by Uman and associates at a Westinghouse facility, Hill could account for about ten percent of the energy dissipation as ohmic heating. The remainder of the energy dissipated is poorly quantified. Among other things, Hill is examining the acoustic dissipation processes.

E. Barreto at the State University of New York has in our program made laboratory observations in an effort to understand certain aspects of the lightning stroke, particularly the propagation and heating of the stroke. His work found application in the investigations of supertanker explosions where the principal effort was an attempt to identify the origin of the incendiary sparks.

D. Tompkins, under ONR support, is continuing work began at the University of Wyoming on the interaction of cosmic ray showers and thunderstorms. He is looking for a presumed characteristic radio emission from the interaction.

H. Bass of the University of Mississippi is attempting, in our program, to correct acoustic signals from thunderstorms for atmospheric molecular absorption. His objective is to work back toward the original shock wave to get a better description of the primary wave.

R. Markson of the Massachusetts Institute of Technology (MIT) and Airborne Associates conducts some theoretical and field work for ONR. His interest in thunderstorm phenomena is closely related to his interest in solar-terrestrial reaction in which he identifies the thunderstorm as the principal mechanism for effecting that reaction as a result of a change in atmospheric conductivity.

The atmospheric electric phenomena of clouds of the subtropics and tropics is comparatively a neglected area of research because of the reluctant acceptance, or rejection, by many scientists of the idea of a cloud being able to separate charge in the absence of an ice phase or supercooled water. ONR has one contract devoted mostly to that problem; T. Takahashi at the University of Hawaii is the principal investigator on that contract.

A recent ONR workshop in AE was held at the University of Wyoming under the direction of D. Hoffman in which measurements of several investigators were compared. A post workshop discussion of these measurements is now underway.

LIGHTNING AS AN INDICATION OF STORM SEVERITY

James C. Dodge

NASA Headquarters

This talk is intended to be a stimulus for future lines of research concerning relationships between lightning occurrence and storm severity.

Compared to the many near-term practical applications which could be made of routine lightning observations from space, the use of such observations to indicate the stage of a storm's development may well seem the most remote; however, recent literature summaries (Golde, 1977; Dolezalke, 1978) include numerous observations that hint at storm-scale, lightning/storm development relationships. Some fairly certain relationships include Vonnegut's 1963 observations that very tall thunderstorms produce far more lightning than storms of ordinary height. Reynolds in 1957 observed that rapid vertical development leads to rapid electric field development. Direct overflights of thunderstorms led Vonnegut to conclude in 1966 that strong electric fields above clouds are observed primarily over penetrative convective cells. Thus, there is a substantial case for the theory that cloud electrification is related primarily to strong convection and the sizeable relative air motions that it implies. It should be pointed out that wind shear is probably essential to such a relative motion mechanism because electrification does occur even in the very shallow, but highly sheared, winter clouds over the Sea of Japan.

This concept of electrification is drastically different in scale from the traditional concepts concerned with cloud microphysics and internal cloud processes such as amount, type, phase, and location of precipitation; aerosol and ion distributions; and 3-D temperature structure.

If strong relative air motions are the principle driver of the electrification process, then one could conceivably relate the electrification, and subsequent discharge rates, to the air motion environments of the thunderstorms. One could then concentrate on larger scale phenomena that have the potential of being observed by satellites. If we could relate the lightning discharge rates, patterns, or characteristics to the observable meso-scale storm environment, including the moisture influx pattern, the surrounding air motions, and the temperature structure, then the satellite observables could be used as indicators of storm severity. It is doubtful that there would be any single relationship which applied to all thunderstorms. Instead, it would be expected that there would be distinct lightning/storm severity relationships for different lattitudes, seasons, and geographical areas.

Currently, the WMO-accepted method for observing and recording thunderstorm occurrence is the isoceraunic contour map. It is simply contours of the average number of days per year that thunder was heard at weather reporting stations. It contains no information on flash rate, flash density, flash relationship to storm severity, or flash variation with meteorological environment, and storm lifetime. The isoceraunic mapping technique also fails in its inability to provide routine observations over oceans, where only personnel on ships-of-chance could hear the thunder. In addition, there is no record of lightning distribution in hurricane rainbands, where intense lightning sometimes has been reported.

Generally, what do we know about lightning/meteorological relationships? Lightning occurs primarily in air mass thunderstorms and squall line thunderstorms with sporadic reports of lightning in hurricane rainbands. To complicate the picture, lightning occasionally occurs in clouds wholly above freezing or very shallow (3 km deep). It seldom occurs without heavy associated precipitation, and it almost never occurs without a continuing moisture influx and a substantial wind velocity shear either in the horizontal or the vertical. It virtually never occurs in the absence of clouds; however, it can strike through the clear air from an upper portion of a cloud to a ground location away from the cloud base.

It seems clear that if data from a satellite-borne lightning mapper were available, we could conduct simultaneous studies of the lightning discharge patterns and the meteorological environments of specific storms. The problem certainly seems worthy of study, especially since lightning discharges are known to be observable from space, and any new information which might help to delineate the development of severe storms could be used by operational forecasters to help refine storm warnings in time and space.

It has been established by Taylor as early as 1973 that the general level (rate) of sferic activity corresponds closely with the severity of a thunderstorm. Similarly, Vonnegut has reported that during the April 1979 tornado outbreak, abnormally high lightning rates were observed by the DMSP satellite over the corresponding thunderstorms.

A constant-view, geosynchronous lightning mapper would afford the opportunity to establish the meteorological relationships. Some of the meteorological studies which would have to be performed relative to establishing any lightning/storm severity relationships include lightning rate related to cloud top height and cloud top growth rate observed from satellites, plan-view precipitation/lightning juxtaposition using radar, identification of regional patterns of electrical cell activation related to the mesoscale environments of storms, and the development of new convective cells related to the direction of electrical activity propagation. Electrical discharge propagation has already been observed by astronauts.

Studies should also continue to relate lightning discharge characteristics to conditions within individual thunderstorm cells. Radar, both conventional and Doppler, should be used to relate flash rate and plan-view location to precipitation amount and velocity. Doppler radars and eventually lidars can help to quantify relationships between wind shear and electrification.

In any case, the mapping of lightning occurrence on a reasonably small scale from a space platform would permit a thorough analysis to establish whether or not there is a reliable enough relationship between lightning discharges and storm severity to use the observed flash rates and characteristics as supplemental guidance for storm forecast refinement.

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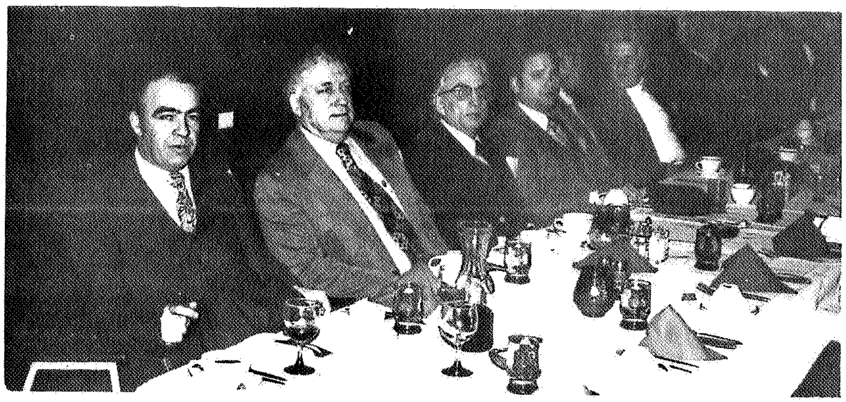
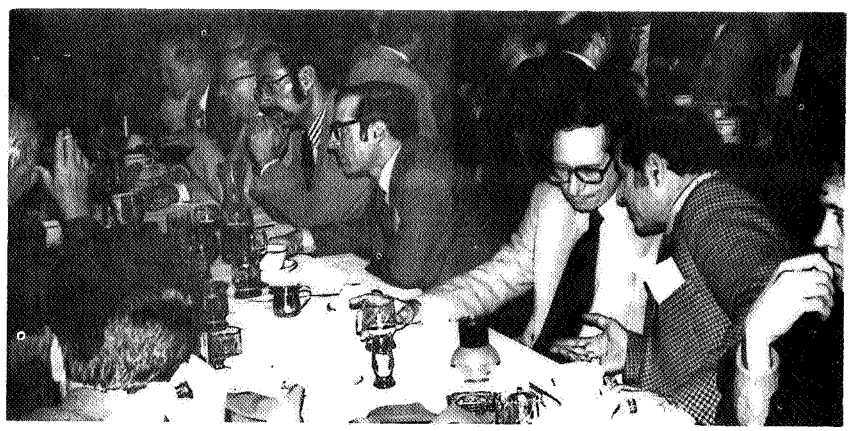
SECTION IV
BANQUET PRESENTATION





PLATFORMS IN SPACE - EVOLUTIONARY TRENDS

John M. Butler, Jr.
NASA Marshall Space Flight Center

The idea of a space platform is certainly not new, as concepts have been around for many years. NASA has done a number of studies of various types of space platforms from time to time in the past, as have many aerospace companies and other groups. However, for one reason or another, none of these studies have progressed to the point of initiation of a hardware program.

It appears that we may now stand on the verge of bringing such an event to pass, and this discussion will elaborate on some of the reasons why this appears to be so. The discussion will deal primarily with trends, and thus will be fairly broad and general in nature. The concepts shown herein are provided merely as representative examples and should not be construed to be more preferable than any other concepts which have been generated.

Figure 1 shows an outline of this discussion. Figures 2 and 3 depict the current Shuttle hardware [Orbiter, External Tank, and Solid Rocket Boosters). The Orbiter shown in Figure 3 is the "Enterprise" which recently underwent vibration tests at MSFC. The Shuttle will be capable of transporting 65,000 lb. of payload to low earth orbit.

The Orbiter must serve as a very versatile vehicle, operating in at least three modes: 1) delivery vehicle, (2) retrieval/maintenance vehicle, and 3) sortie vehicle. Figure 4 depicts a maintenance mission wherein an earth resources payload is being retrieved into the Orbiter bay for replacement of modules. A payload delivery would look very similar to this, with the Remote Manipulator System (RMS) being utilized in that case to release the payload instead of to retrieve it. With the activation of the Orbiter, we stand on the threshold of exploitation and utilization of space, in much the same manner as the pioneer families stood on the threshold of settling the West. Just as they had been preceded by explorers, trappers, and hunters, we have sent out our Mercuries, Geminis, Apollos, and Skylabs and are now ready to move into a more comprehensive mode of operation. In this context, the Orbiter is somewhat analagous to the covered wagon used by the pioneers - it must serve as vehicle, home, and fortress against the elements.

The Orbiter may be thought of as a sort of early "platform" in space in that it serves as a station from which space operations are carried on, especially in its sortie mission mode. as depicted in Figure 4a. However, the Orbiter must return to earth at the end of each mission, whereas a space platform of the type which will be discussed

FIGURE 1

SPACE PLATFORMS

- WHERE WE ARE NOW
- THE FAR END OF THE SPECTRUM
- STEPS TO BE TAKEN BETWEEN HERE AND THERE
- TYPICAL PAYLOAD DATA NEEDED

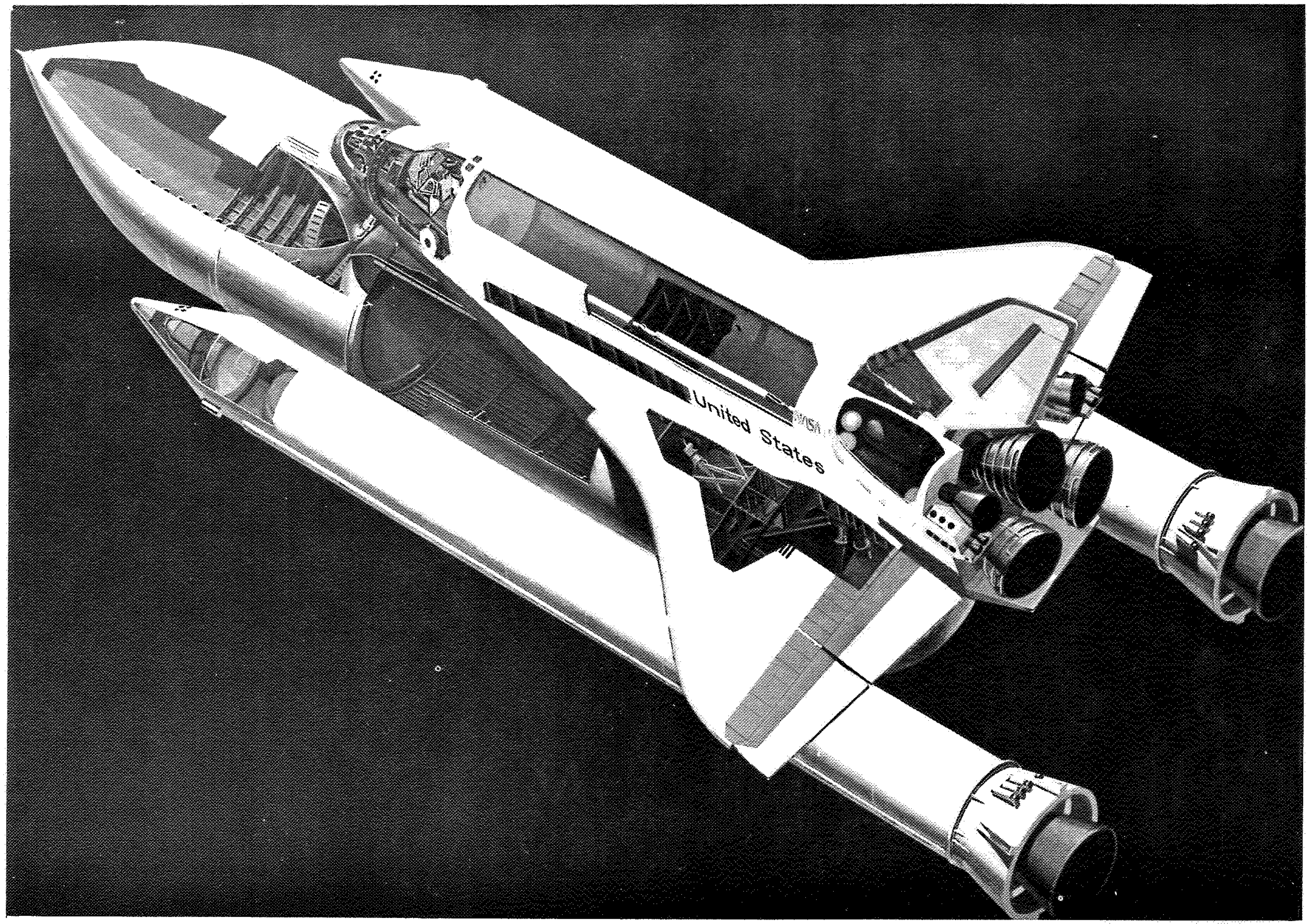


FIGURE 2. CURRENT SHUTTLE HARDWARE.

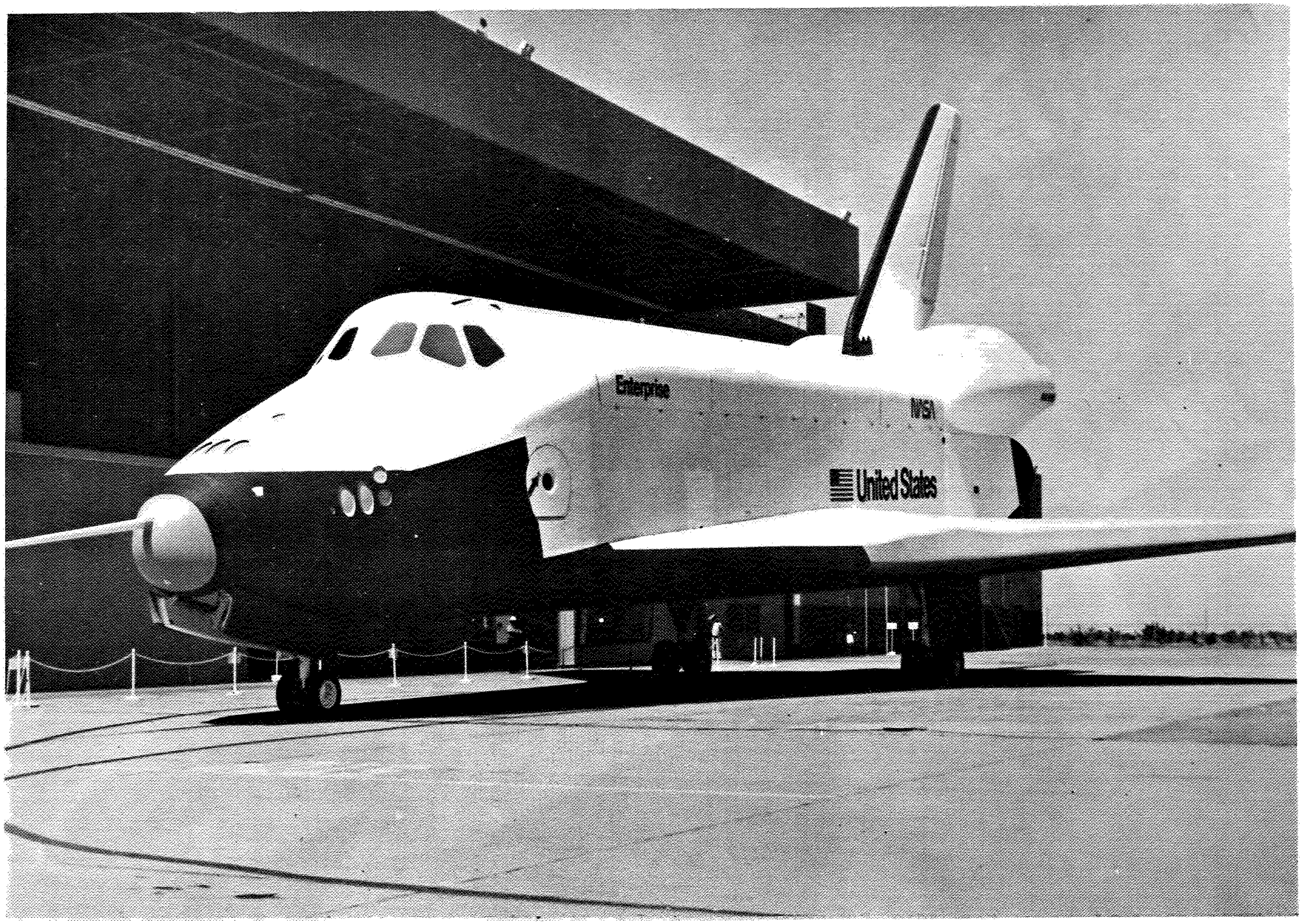


FIGURE 3 "THE ENTERPRISE."

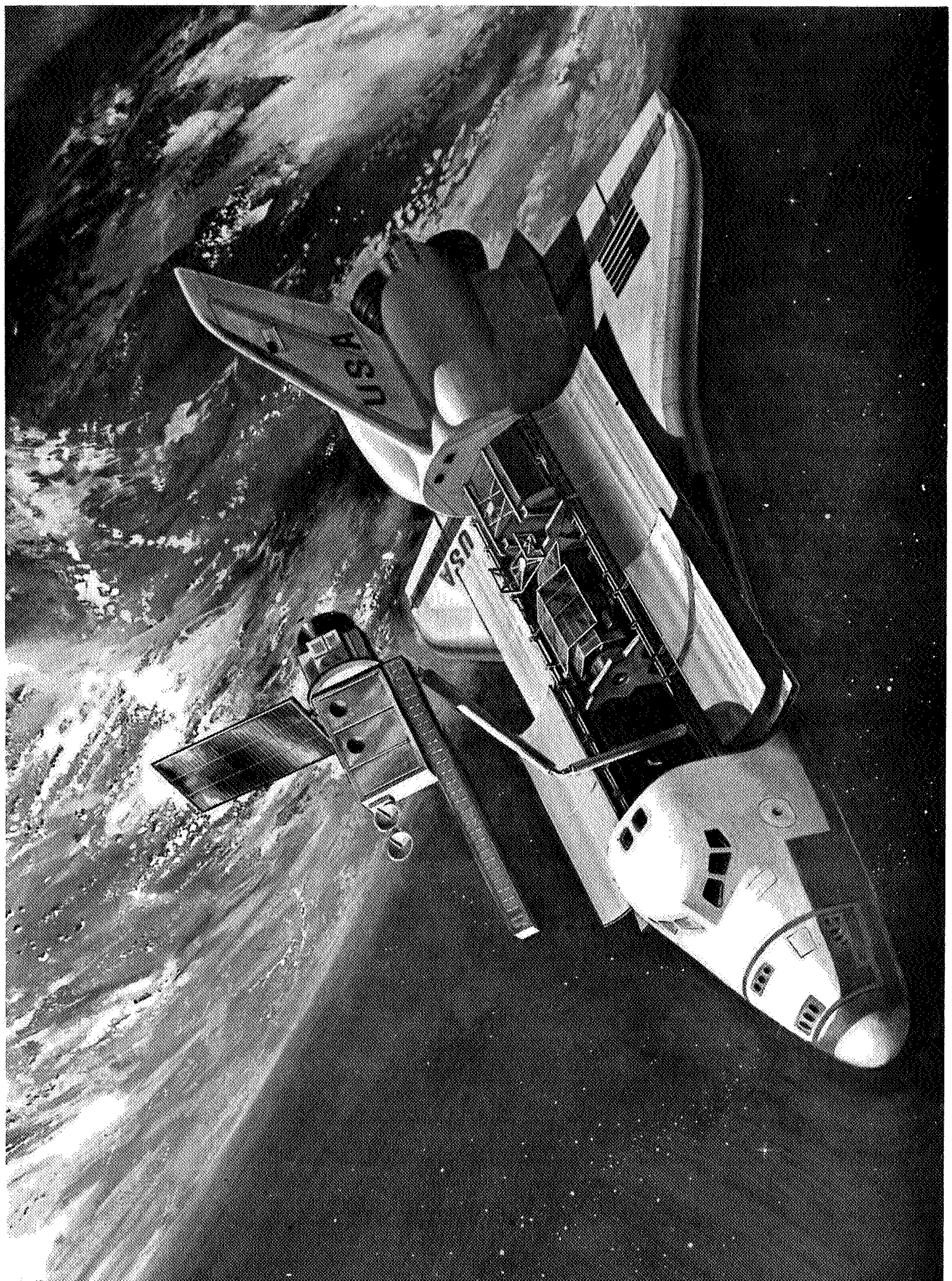


FIGURE 4. MAINTENANCE MISSION: RETRIEVAL OF AN EARTH RESOURCES PAYLOAD INTO THE ORBITER BAY.

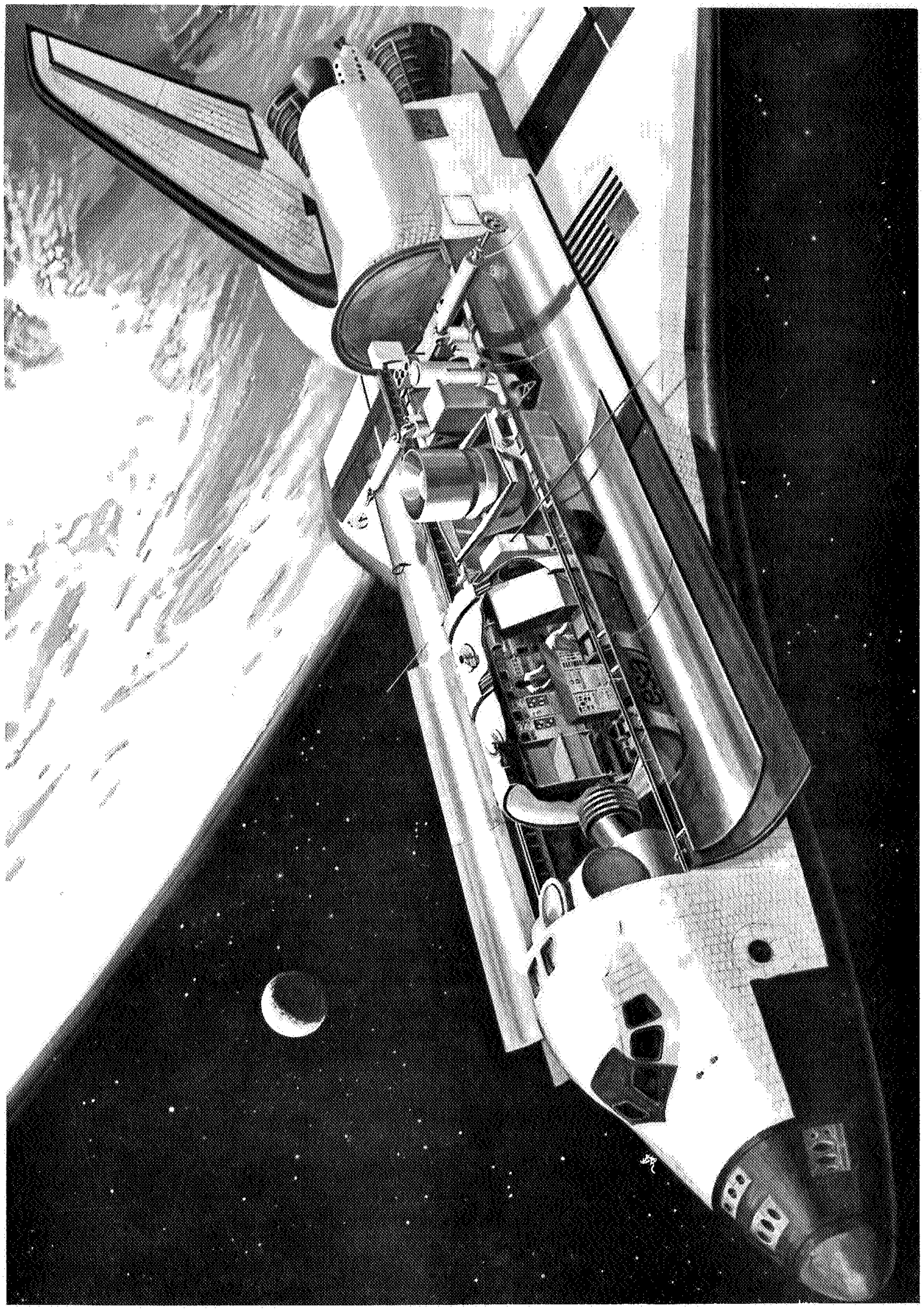


FIGURE 4a SORTIE MISSION MODE

herein would remain permanently on orbit. There is a need for the Orbiter to continue operations in its multi-faceted role for many years to come, even after the advent of space platforms. However, there are limitations in utilizing the Orbiter which a space platform could alleviate significantly. Transportation costs could be decreased significantly if some or all of the payload could be left on orbit rather than having to round-trip it. The Orbiter presently has limitations on stay-time in orbit and on power available to payloads, which could be alleviated with a platform. Also, a more quiescent environment can be achieved away from the Orbiter, as on a space platform.

Looking now at a representative type of space platform on the far end of the scale, Figure 5 shows a Solar Power Satellite (SPS) which would be several kilometers long and hundreds of meters wide. One of its two power-producing wings is shown here, with a microwave antenna array in the foreground. This satellite would generate about 5 gW of power which would be beamed down via microwave to a ground rectenna. Habitability modules are shown attached to the structure, and a construction module is shown manufacturing a beam for use in constructing space structures. Such a platform would weigh tens of thousands of kilograms, and thus a "Heavy Lift Launch Vehicle (HLLV)" might also have to be a part of such a program to provide cheaper transportation to space. We are investigating structures which are deployable as well as those which are manufactured in space. It is probable that the early ones will be deployable, but the larger (later) ones may have to be built in space to be cost-effective. Such large platforms as this one are studied from time to time to drive out technology requirements, to determine feasibility of concepts, and to help establish programmatic content and direction.

Jumping back now to some of the platform concepts which are likely to exist in the nearer future, Figures 6 - 9 deal with geosynchronous satellites. Figure 6 shows the C-band satellites which are presently on orbit at geosynchronous altitudes. As can be seen, this region is becoming very crowded, and this trend is expected to accelerate as more and more foreign countries, as well as the United States, have geosynchronous satellites. Typically, about four degrees of physical separation must be maintained between these satellites to enable ground station discrimination of individual satellite signals. Figure 6 also shows the locations of four platforms which might possibly be used to group these satellites, and Figure 7 indicates the specific satellites which might be on each platform.

Figure 8 depicts what such a platform might look like. The largest antenna is about 30 M. diameter; there are several about 10-12 M., some at 4-5 M., and other smaller ones also. The platform must have larger diameter antennas than individual satellites so that the smaller beam widths will allow discrimination of individual beams from the ground even though the antennas are close together. In addition to the physical crowding problem, another significant problem associated with

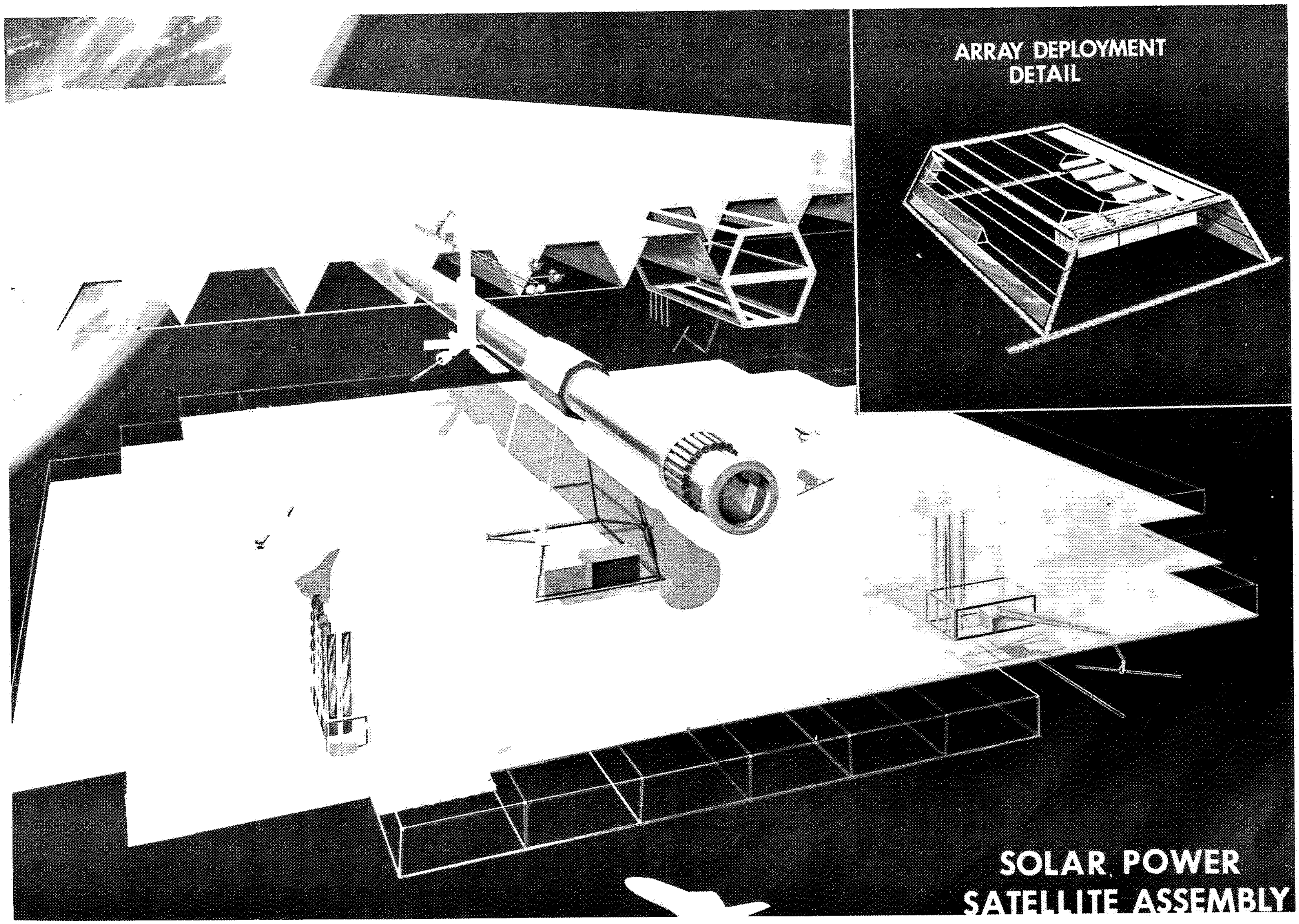


FIGURE 5. SOLAR POWER SATELLITE.

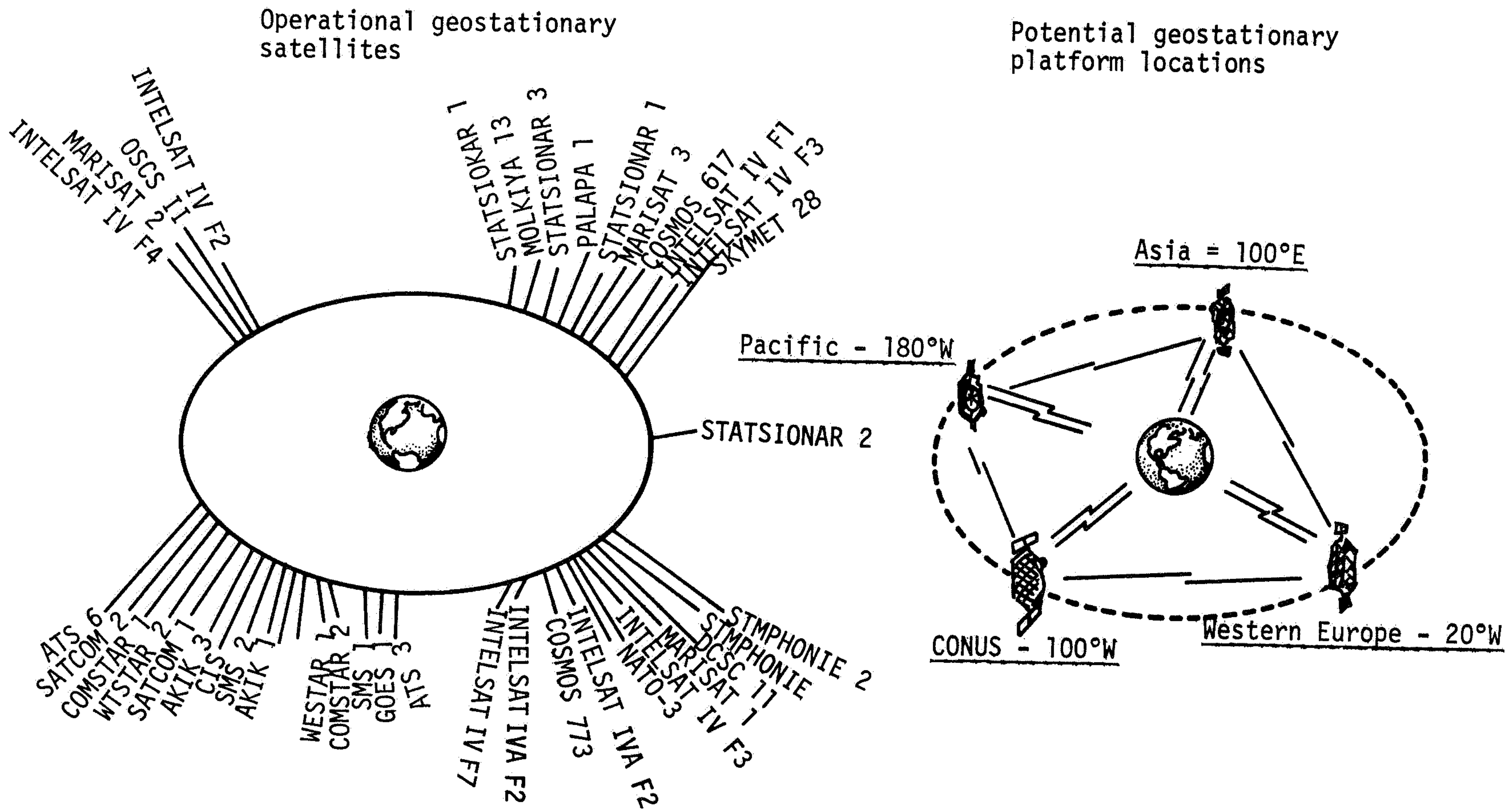
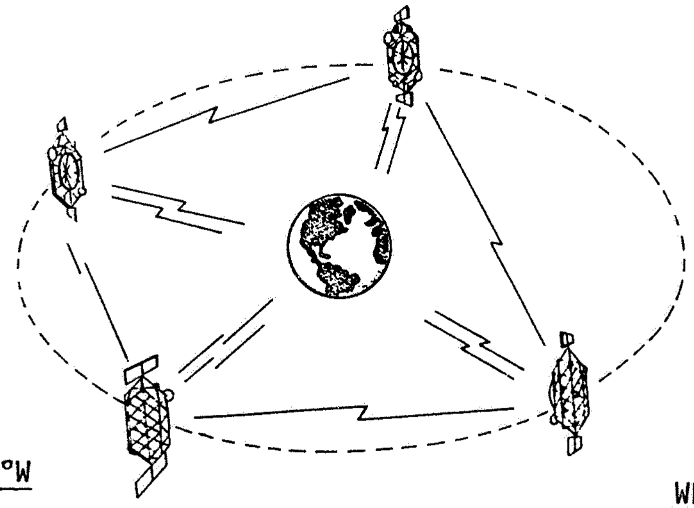


FIGURE 6. GEOSTATIONARY PLATFORM.



PACIFIC -- 180°W

TDRSS
INTELSAT VI
MARISAT
INMARSAT
INATSAT
INSAT
CS F/O
BSE F/O
GMS F/O

ASIA -- 100°E

MARISAT
ARCOMSAT
IRAN F/O
PALAPA F/O
INTELSAT VI

CONUS -- 100°W

COMSTAR F/O
WESTAR F/O
RCA F/O
ASC
SBS
PUBLIC SERVICE
IMAGE TRANSMISSION
HI CAP VIDEO
SEOS*
PUBLIC SERVICES R&D*
ORBITING STANDARDS PLATFORM*
OTHER US
DISASTER WARNING
BRAZILSAT F/O
TELSAT F/O
UHF
CANADIAN DIRECT B/C
U.S. GOVT EARTH RES
PRIVATE INDUSTRY EARTH RES
GEOSYNC R&D WEATHER SAT (STORMSAT)*
HAZARD WARNING/COMMUNICATIONS SAT*
SYSTEM '85 OPER SAT (GOES)*

WESTERN EUROPE -- 20 W

INTELSAT VI
TDRSS
MARISAT
INMARSAT
INATSAT
ECS F/O
TV BROADCAST F/O
SIRO F/O
NORDSAT F/O
NATO F/O
METEOSAT
ESA E.R.

*Based on NASA payload data bank being developed in conjunction with OSTA. All other payloads are from the "Outside Users Model" (Battelle) dated Aug. 1977.

FIGURE 7. GEOSTATIONARY PLATFORM: CANDIDATE PAYLOADS.

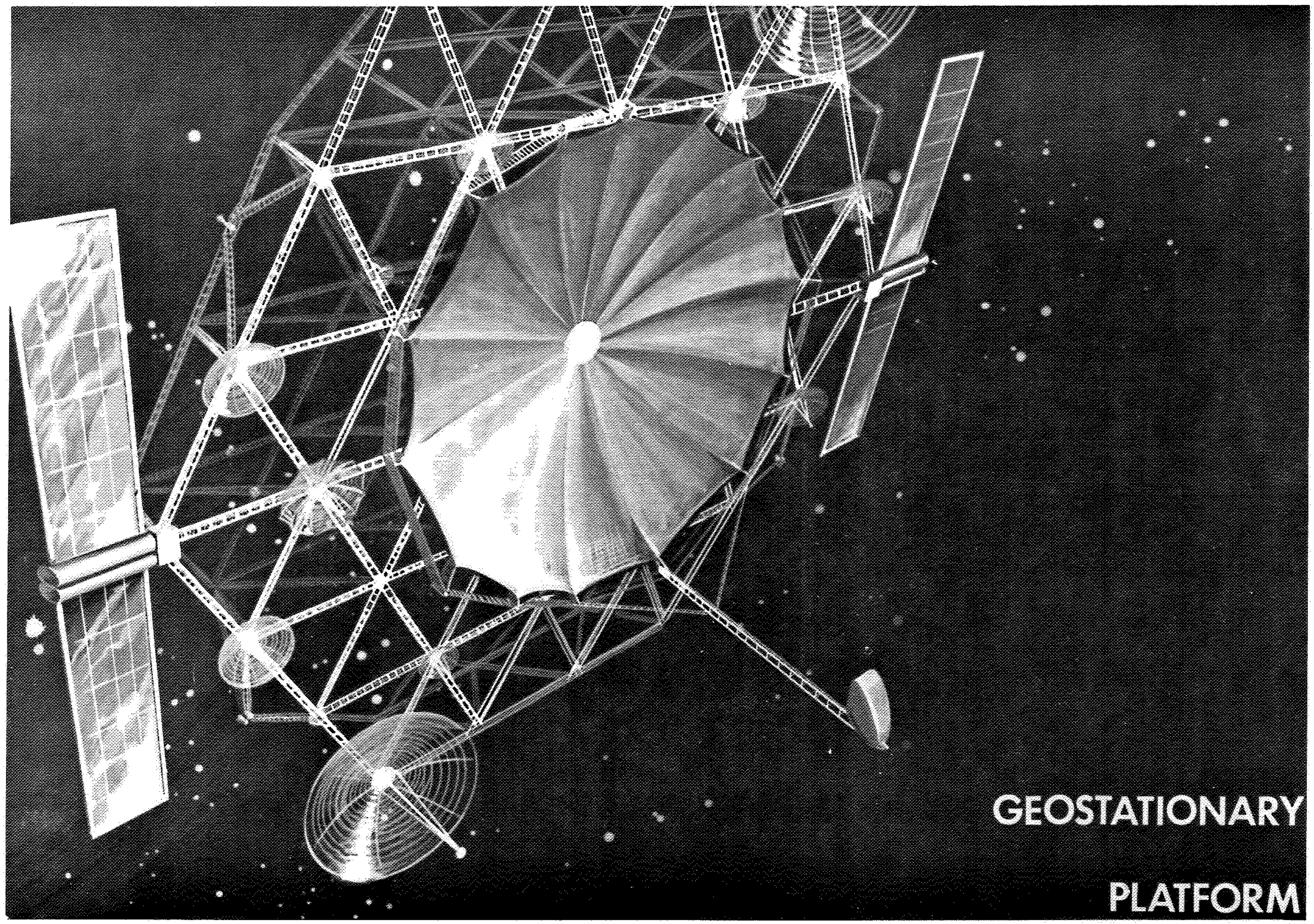


FIGURE 8 POSSIBLE GEOSYNCHRONOUS PLATFORM.

multiple free-flying satellites is the proliferating number of separate communication links required. This problem can be relieved significantly by using platforms and multiplexing the data streams. Significant decreases in duplication of satellite support systems can also be eliminated with platforms, thereby reducing hardware costs and transportation costs. Figure 9 depicts a representative revisit of a platform. Here, the Orbiter would go up to low earth orbit; then an Orbit Transfer Vehicle (OTV) would transport a remote exchanger device (shown here as the Teleoperator) and exchangeable modules to the geosynchronous platform. Having platforms would significantly decrease revisit costs compared to having a revisit for each separate satellite.

Figure 10 depicts an early step in progressing towards the large space structures needed for large platforms. Here a beam machine is being utilized to manufacture beams on orbit, which are then assembled into an early element of the SPS platform.

Something has occurred within NASA in the last two or three weeks which might very well be the key decision leading to the next step we must take along the road to a space platform. Dr. Frosch signed a letter in late January which gave responsibility to MSFC for a free-flying Power Module (PM), which could be developed and flown in the 1983-1984 time frame, given proper funding. The PM has as a primary design requirement the ability to support the Orbiter and its payload in the sortie mode, supplying power (25 KW) and attitude control (using control moment gyros) for the combined orbiting assembly. The PM would be left on orbit when the Orbiter returns to Earth, and in this mode, with payloads attached, the PM can become the first of NASA's space platforms. Other PM's can be utilized on dedicated platforms with groups of payloads in various orbits, as requirements dictate. The term Power Module is somewhat misleading, since the present concept of the PM is a module which can provide not only power but also attitude control, limited heat rejection, some communications, and a docking interface for free-flying payloads. Figure 11 is a concept of the PM with a free-flying payload in low earth orbit.

Figure 12 shows some of the early building blocks which might be utilized to derive various types and sizes of platforms. Some of these elements are for pressurized payloads and some are for non-pressurized ones. In the unpressurized concepts, the structural trusses are attached to the docking ports on the support module, forming "arms" to which pallets can be attached. In the pressurizable concepts, the pressurizable payload modules would be attached directly to the pressurizable support module without using "arms." Various potential combinations of these building blocks are shown on the right and bottom sides of Figure 12.

Figure 13 represents one of the earliest potential platforms which could be flown. Three disciplines are shown accommodated here. The arm of the platform containing the earth-viewing pallet could have a rotating

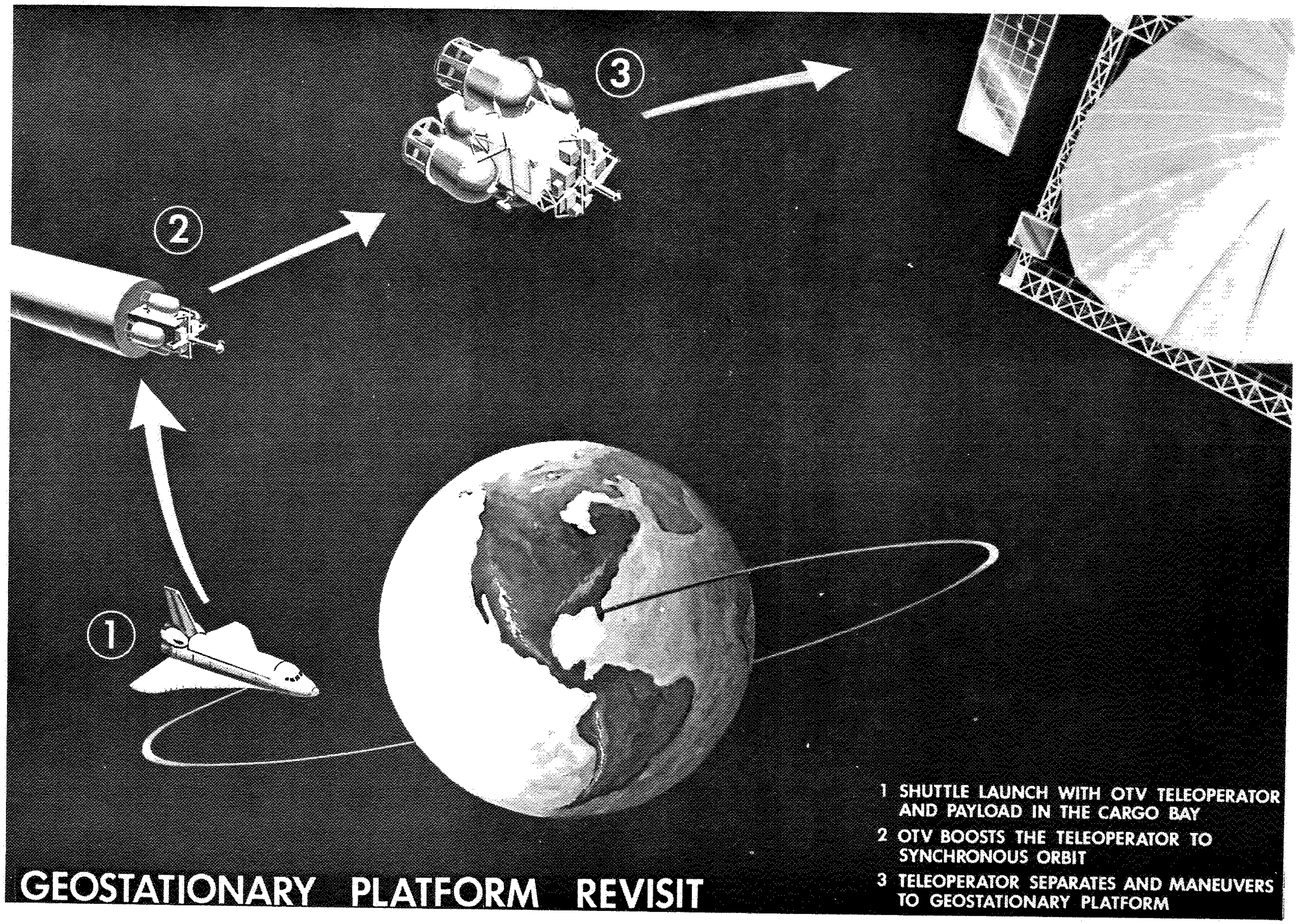


FIGURE 9 REPRESENTATIVE REVISIT OF A PLATFORM.

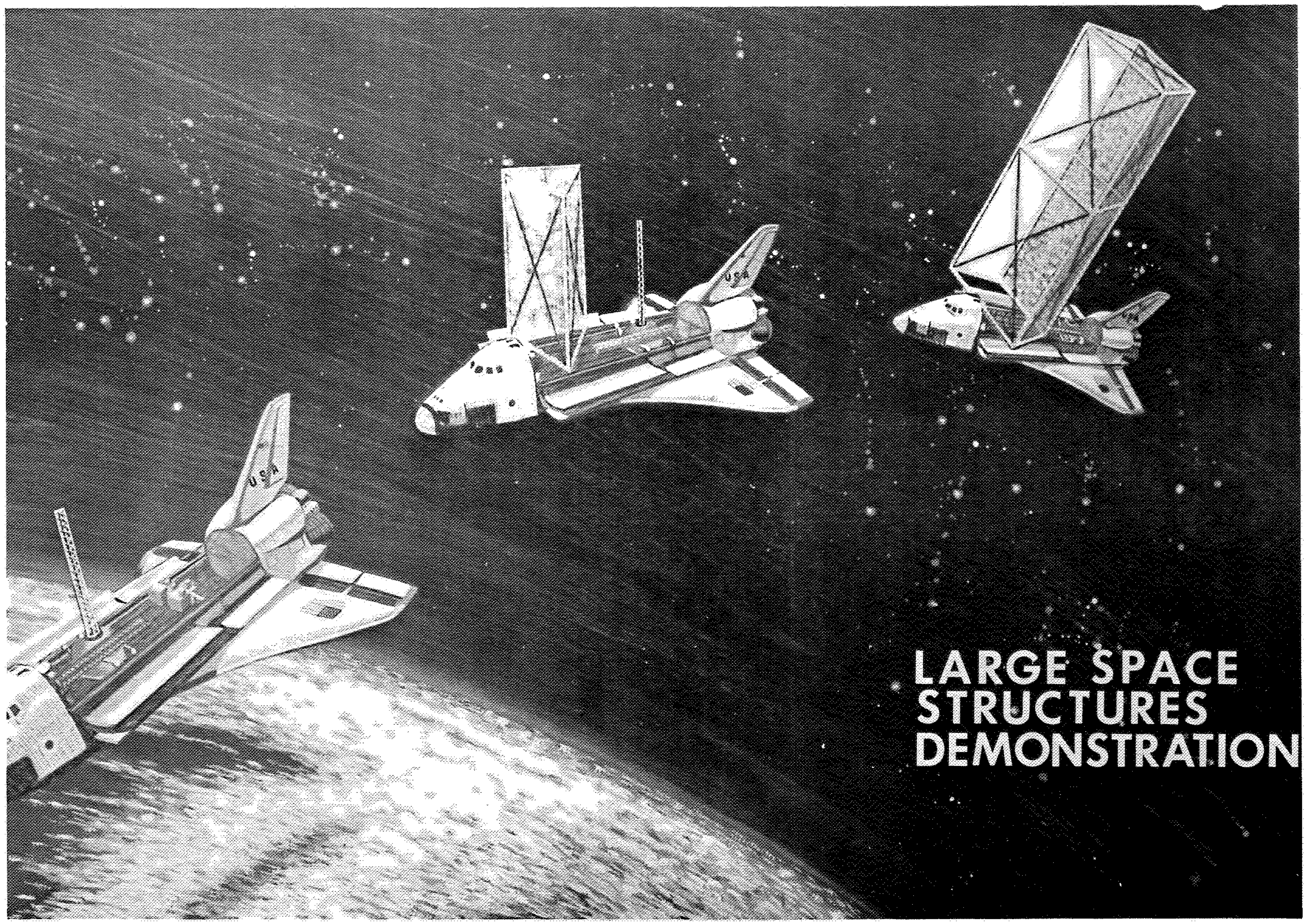


FIGURE 10. AN EARLY STEP TOWARDS LARGE SPACE STRUCTURES: USING A BEAM MACHINE TO MANUFACTURE BEAMS ON ORBIT.

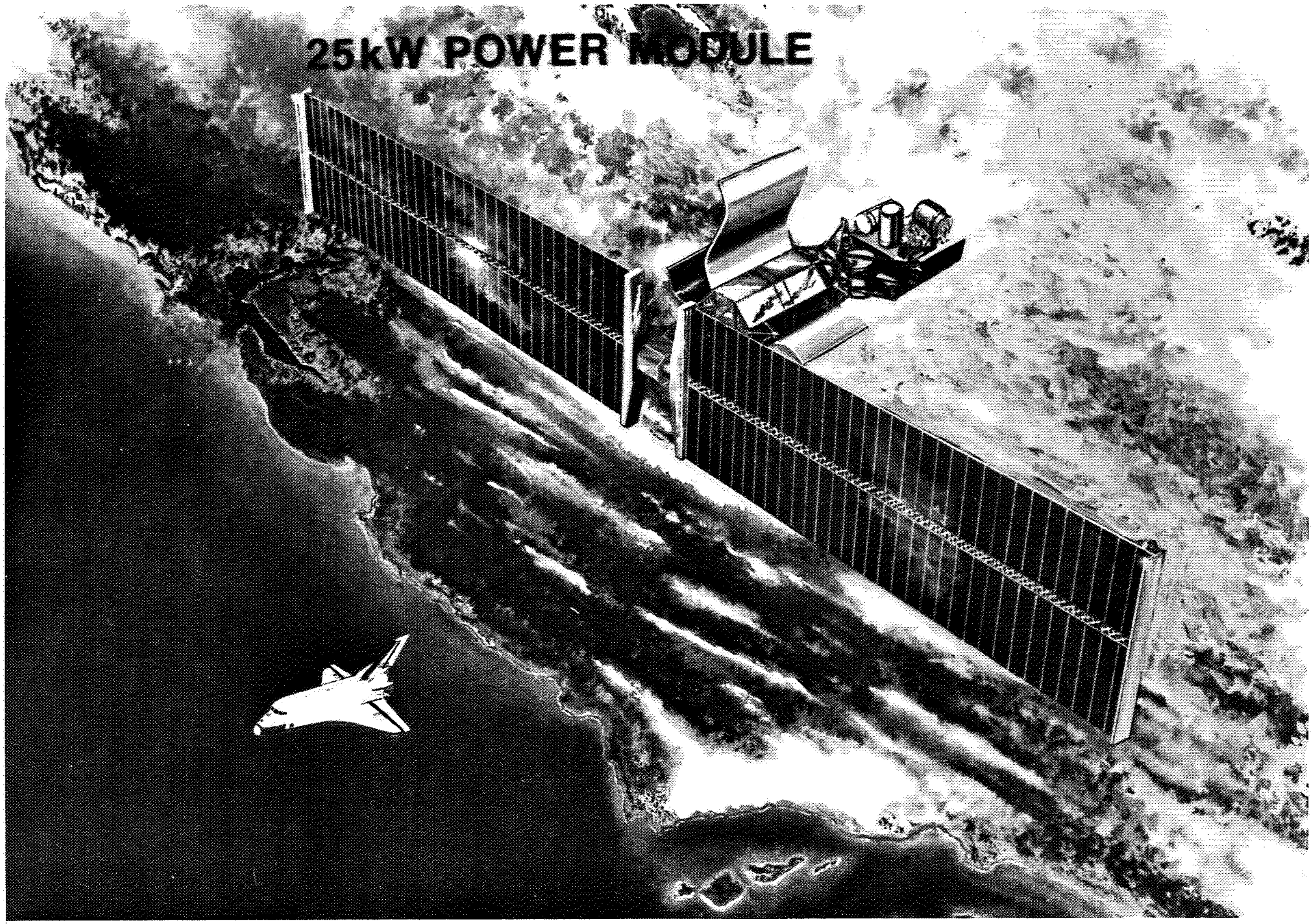


FIGURE 11. POWER MODULE WITH FREE-FLYING PAYLOAD IN LOW EARTH ORBIT.

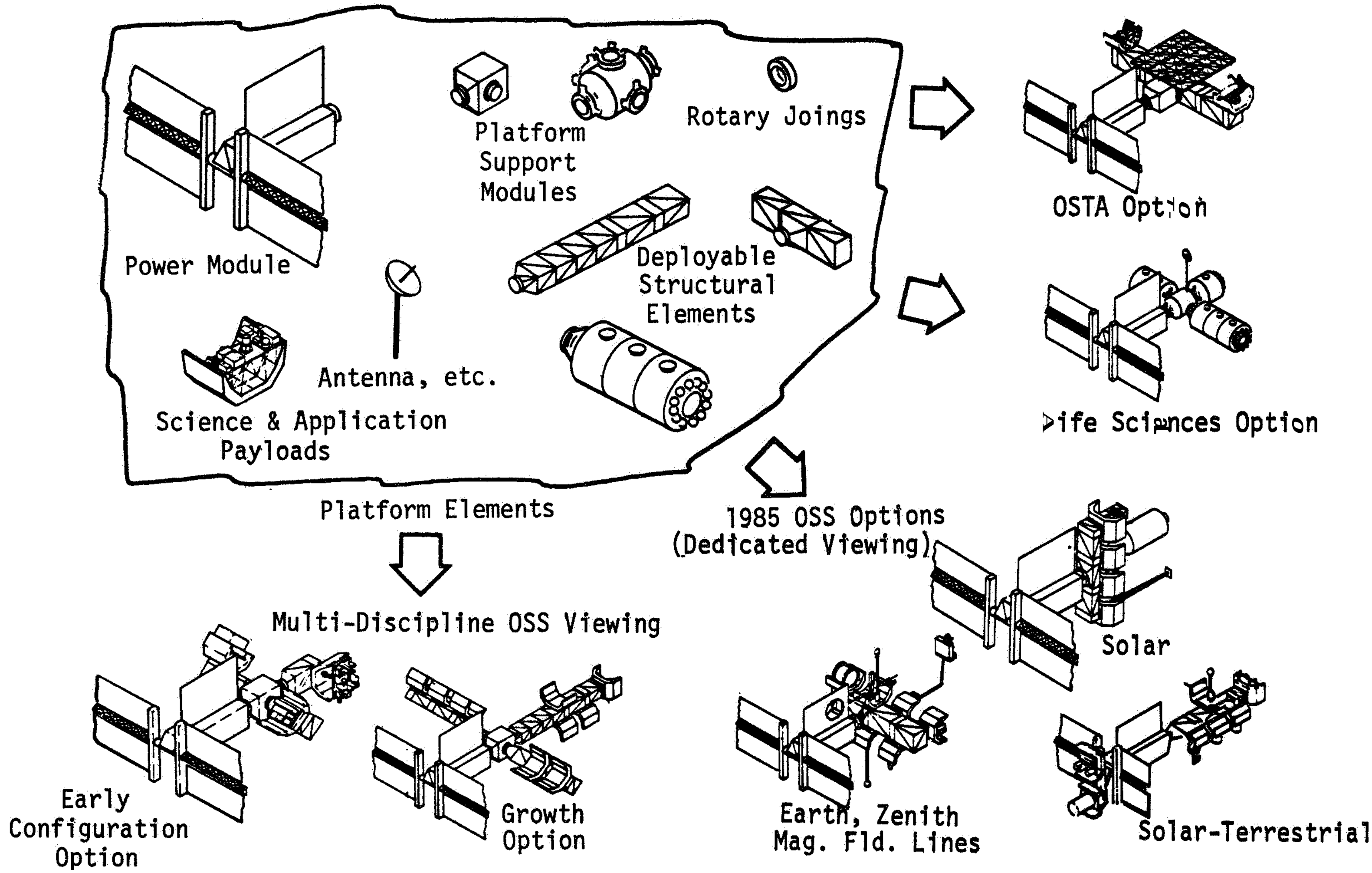


FIGURE 12. SCIENCE AND APPLICATIONS SPACE PLATFORM MODULAR BUILD-UP OPTIONS.

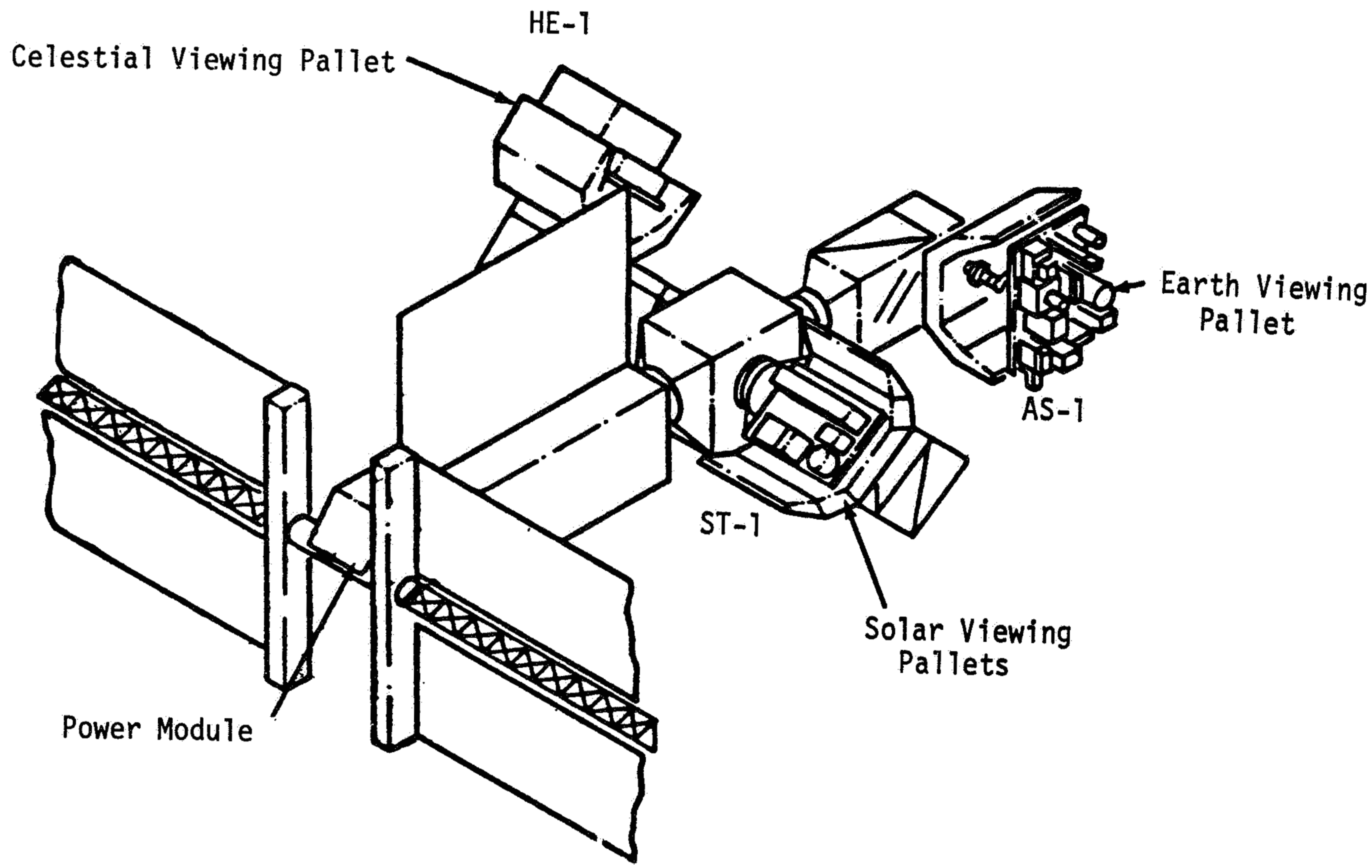


FIGURE 13 SCIENCE AND APPLICATIONS SPACE PLATFORM EARLY MULTI-DISCIPLINE CONCEPT.

joint allowing it to rotate at earth-rates while the remainder of the platform remained at a fixed orientation (long axis-POP, for example) with respect to the orbit plane.

The other two arms could have rotating joints, if desired, An alternative approach would be for all arms to have fixed joints rather than rotating joints, and the platform orientations could then be varied from "semi-inertial" to earth-fixed ones on a time-shared basis to provide priority viewing for each user on a time-shared basis. Still another approach would be to have an entire platform (rather than merely an arm) dedicated to a given discipline, and to provide platform orientation for that discipline with no time-sharing required,

By way of information, there is another piece of Orbiter support hardware in the planning stages, for which JSC has recently been given the present responsibility. This element is called the Power Extension Package (PEP), and is essentially a solar array which is planned to be round-tripped with the Orbiter to augment its orbital stay-time and possibly its power level. Thus, in the early- to mid-1980's, users might be able to select from a wider set of hardware combinations for shorter duration sortie missions also.

One payload which has been proposed for flight on Orbiter sorties and on a platform is the "Tether" payload, which might be of particular interest to this workshop. The Tether payload consists of a cluster of instruments mounted in a spherical housing which would be extended from the Orbiter or platform towards the earth in a gravity gradient mode, on a multi-kilometer long tether. The instruments could possibly be "dragged" through the upper regions of the ionosphere to make electrical field measurements, and data in the regions above thunderstorm activity could be taken.

Figure 14 summarizes some of the key advantages of utilizing a space platform. This is not to say that all payloads can or should be placed on a platform. There are many payloads and/or missions which simply will not be feasible to consider for implementation on a platform. But for the ones which can be thus implemented, a considerable increase in cost-effectiveness should be realized.

The next three charts show the type of payload requirements data which is needed to allow meaningful study of payloads as candidates for platform implementation. Figure 15 is a printout of the data used on a recent inhouse MSFC platform study of OSS and OSTA payloads. The data items listed here are some of the same ones that are included on the blank data sheets handed out at the beginning of this conference. Figure 16 shows how this data can be used to help determine what the size and capability of a platform should be. For example, for this particular set of payloads, 90% of them could be accommodated if the platform power distribution capability to each payload were sized for about 3 KW. Figure 17 lists some of the key factors affecting compatibility and

FIGURE 14

SPACE PLATFORM ADVANTAGES

- COMPARED TI) SORTIES
  - LONGER DURATION ON ORBIT
  - MORE ELECTRICAL POWER TO USERS
  - LESS ROUND-TRIPPED WEIGHT
  - MORE QUIESCENT ENVIRONMENT
- COMPARED TO FREE-FLYERS
  - LESS DUPLICATION OF HARDWARE
    - LOWER HARDWARE COSTS
    - LOWER LAUNCH COSTS
  - LESS CONGESTION IN ORBIT
    - SPATIAL CONGESTION
    - COMMUNICATION CONGESTION
  - LOWER REVISIT COSTS

FIGURE 15

TYPICAL REQUIREMENTS OF OSS PAYLOAD ELEMENTS

TODAY'S DHTE =1-8-79

PLD NO	PLD NAME	AVAIL DATE	VIEW TYPE	L.LIM INCL	PREF INCL	U.LIM INCL	PTG MOUNT	AV PWR (KW)	DA RATE (BPS)
S	FALX0	1981	4	28	28	57	0	0.29	1 10E+06
AST-1	PAL#1	1982	5	28	28	57	1	1 00	2 00E+05
AST-2	PAL#2	1384	5	28.	28	90	1	0.20	1 00E+02
AST-3	PAL#3	1387	5	28	57	98	1	1 00	1 00E+06
AST-6	SIRTF	1385	5	28	28	90	1	5 00	3,00E+06
AST-7	S.LAB	1987	5	28	28	57	1	1 30	2 00E+06
AST-8	A.TEL	1988	5	28	28	57	1	1 50	1.00E+06
HE-1	PAL#1	1983	5	28	28	28	~~1~~	~~0.40~~	6.00E+04
HE-2	PAL#2	1985	4	57	70	90	0	0.20	1 00E+05
HE-3	PAL#3								
HE-4	PAL#4								
HE-5	PAL#5								
HE-11	LAMAR								
HE-12	A.CRO								
HE-13	LAMAR								
SP-1	PAL#1								
SP-2	PAL#2								
SP-3	PAL#3								
SP-4	PAL#4								
SP-5	PAL#5								
SP-9	SOT								
SP-10	PHC-1								
SP-11	SCADM								
SP-12	PHC-2								
SP-13	SO.XR								
AS-1	PAL#1								
AS-2	PAL#2								
AS-3	PAL#3								
AS-7	TETHR								
AS-9	CLIR								
125-18	LIDAR								
SPP-1	PAL#1								
5PF-2	PAL#2								
SPP-3	PAL#3								
SPP-6	S.SAT								
CPF-7	W.PAR								
SPF-8	R BEL								
SPP-9	CRM								

VIEW TYPE: 1 S

TODAY'S DATE: 1-8-79

PLD NO	PLB NAME	LCH DHTE	ON-OPR WT(KG)	HLT (KM)	INCL (DEG)	FTG ACC (SEC)	STAB (SEC)	AV PWR (KW)	DA RAT (BPS)
SL-2	SL-2	1981	2525	400	28	3 60E+03	3 60E+02	0.29	1 10E+06
AST-1	PAL#1	1982	578	400	28	1 00E-01	1 00E-02	1 00	2 00E+05
HST-2	PAL#2	1984	1000	300	28	5 00E 01	2 00E-01	0.20	1 00E+02
HST-3	PAL#3	1987	3500	400	57	3.00E+01	3 00E+00	1 00	1 00E+06
AST-6	SIRTF	1985	2500	350	28	1 00E+00	1 00E-01	5 00	3.00E+06
AST-7	S.LAB	1987	2000	300	28	1 00E+00	1 00E-02	1 30	2 00E+06
AST-8	A.TEL	1988	3000	350	28	1 00E-03	1 00E-03	1 50	1 00E+06
HE-1	PAL#1	1983	1100	400	28	3 60E+02	3.60E+91	0.40	6 00E+04
HE-2	PAL#2								
HE-3	PAL#3								
HE-4	PAL#4								
HE-5	PAL#5								
HE-11	LAMAR								
HE-12	A CRO								
HE-13	LAMAR								
SP-1	PAL#1								
SP-2	PAL#2								
SP-3	PAL#3								
SP-4	PAL#4								
SP-5	PAL#5								
SP-9	SOT								
SF-18	PHC-1								
SP-11	SCADM								
SP-12	PHC-2								
SP-13	SO XR								
RS-1	PAL#1								
HS-2	PAL#2								
AS-3	PAL#3								
AS-7	TETHR								
AS-9	CLIR								
AS-18	LIRHR								
SPP-1	PAL#1								
SFP-2	PAL#2								
SFF-3	PAL#3								
SPP-6	S.SAT								
SPP-7	W.FAR								
SPF-8	R.BEL								
SPP-3	CRM								

TODAY'S DHTE =1-8-79

PLD NO	PLD NAME	AVAIL DATE	VIEW TYPE	L LIM INCL	PREF INCL	U.LIM INCL	PTG MOUNT	AV PWR (KW)	DA RATE (BPS)
SL-2	PAL#0	1981	4	28	28	57	0	8.29	1 10E+06
AST-1	PAL#1	1982	5	28	28	57	1	1 00	2,00E+05
AST-2	PAL#2	1984	5	28	28	98	1	1?.28	1 00E+02
AST-3	PAL#3	1987	[illegible]	28	[illegible]	90	1	1 00	1 00E+06
HST-6	SIRTF	1985	5	28	28	90	1	5.88	3 00E+06
HST-7	S LAB	1987	[illegible]	28	28	57	1	1 38	2 00E+06
AST-8	A TEL	1988	5	28	28	57	1	1 50	1 00E+06
HE-I	PAL#1	1983	5	28	28	28	1	8.40	6 00E+04
HE-2	PAL#2	1985	4	57	70	90	0	0 28	1 00E+05
HE-3	PAL#3	1986	5	28	28	28	1	8.38	3 20E+04
HE-4	PAL#4	1988	4	28	28	28	0	0 12	1 00E+04
HE-5	PAL#5	1939	5	28	28	28	1	0 10	3 00E+03
HE-I1	LAMAR	1986	5	28	28	28	1	e 24	5 00E+04
HE-12	A.CRO	1'387	4	28	28	38	0	1 10	1 00E+05
HE 13	LAMAR	1988	5	28	28	28	1	0 48	5,00E+04
SP-1	PAL#1	1982	1	28	90	90	1	e 25	6,00E+05
SP-2	PAL#2	1983	1	28	Si	90	1	0 67	2,50E+05
SP-3	PAL#3	1986	1	28	38	90	1	0,20	1 20E+06
SP-4	PAL#4	1988	1	28	90	90	1	0,20	2 40E+06
SF-5	PAL#5	1989	1	28	98	90	1	0.40	2 00E+06
SP-9	SOT	1984	1	28	98	98	1	1 60	1 40E+07
SP-18	PHC-1	1385	[illegible]	29	90	90	1	0.50	4.00E+05
SF-11	SCADM	1986	1	28	98	98	1	1 50	4,00E+05
SF-12	PHC-2	1988	1	57	90	90	1	0.50	4 00E+05
SP-13	SO XR	1989	1	28	90	90	1	0,35	2.40E+06
AS-1	FALX1	1984	2	21	70	90	1	0.50	4,00E+06
AS-2	PAL#2	1987	2	28	28	9s	1	1 50	7,00E+06
HS-3	PAL#3	1990	2	28	70	90	1	1 50	7,00E+06
SPP-1	PAL#1	1982	3	57	78	90	1	0.50	4 00E+06
SPP-2	PAL#2	1982	6	57	70	90	0	0.10	1 00E+06
SPF-3	PAL#3	1985	3	57	70	90	1	0,25	3.00E+05
ST-1	PAL#1	1985	1	57	70	98	1	0.93	8.50E+05
ST-2	PAL#2	1985	2	57	78	90	1	1 10	3,50E+06
ST-3	PAL#3	1985	4	57	70	90	1	3,70	4 40E+06
ST-4	PAL#4	1988	1	57	70	90	1	3,50	1 40E+06
0	0	0	0	0	0	0	0	0.00	0 00E+00
9	0	0	0	0	0	0	0	0.08	0 00E+00
0	0	0	0	0	0	0	0	e.00	0.00E+00

VIEW TYPE: 1 SOLAR, 2 EARTH, 3. MAG FLD LINES, 4 ANTI-EARTH, 5.CEL, 6.OTHER

FIGURE 16

OSS PAYLOAD ELEMENT REQUIREMENTS

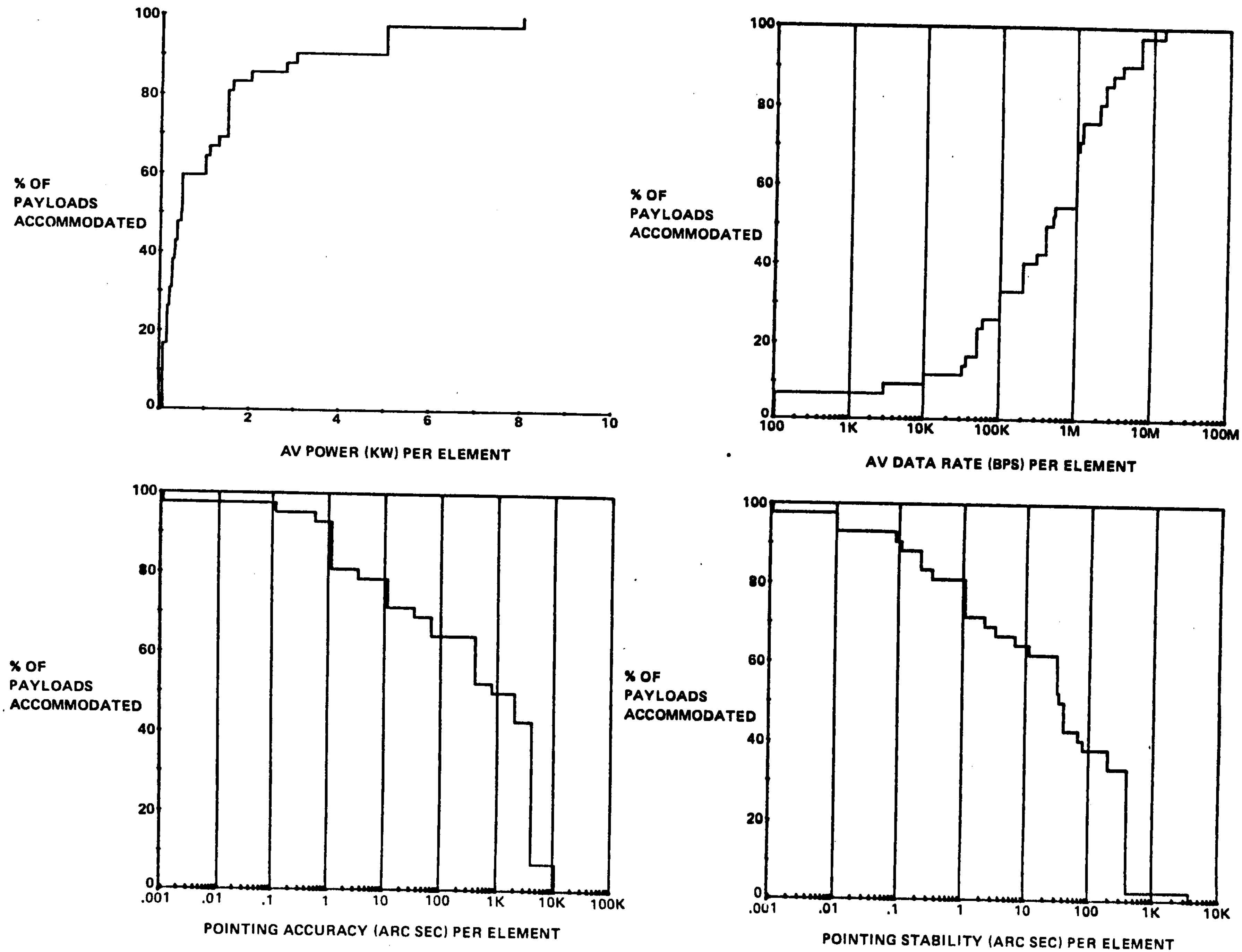


FIGURE 17

FACTORS AFFECTING COMPATIBILITY/GROUPING OF PAYLOADS

- SCIENCE OBJECTIVES
- RESOURCE NEEDS:
  - POWER
  - DATA RATES
  - HEAT REJECTION
  - POINTING CONTROL
- PHYSICAL CONFIGURATION/SIZES
- FIELDS OF VIEW
- ENVIRONMENTS (SUSCEPTIBILITY AND GENERATION)
  - CONTAMINATION
  - g-LEVEL
  - RADIATED ENERGY (ELECTROMAGNETIC AND IR INTERFERENCE)
- ORIENTATION NEEDS
- ORBIT REQUIREMENTS:
  - ALTITUDE
  - INCLINATION
  - β ANGLE
  - GROUND TRACE
- SEASONAL CONSTRAINTS
- MISSION DURATION AND REVISIT REQUIREMENTS
- SCHEDULES AND COSTS

grouping of payloads on a platform. Data relating to these areas is needed for each payload to be assessed properly for platform application.

Further studies of platforms are now being planned for late spring or summer of this year (1979). These studies will involve OSS, OSTA, and OSTS elements at NASA Headquarters. NASA's current interest in platforms should be evident, and any data on payload requirements derived from this workshop could be fed into such a study.

In the platform study just completed by MSFC, there was a high degree of user interest and participation, and we are very serious about interacting more with the user in the early stages of the design studies than perhaps has been done in the past. As the users evaluated some of the initial platform concepts which had been generated, several types of comments seemed to be prevalent throughout their assessment. Some of these key thoughts were that we should keep the platform simple and cheap, and that we should utilize "building block" approaches like "tinkertoys." In trying to satisfy the users' desire thus expressed, someone has come up with a concept which perhaps interpreted the users' comments too literally. This concept is shown as Figure 18.

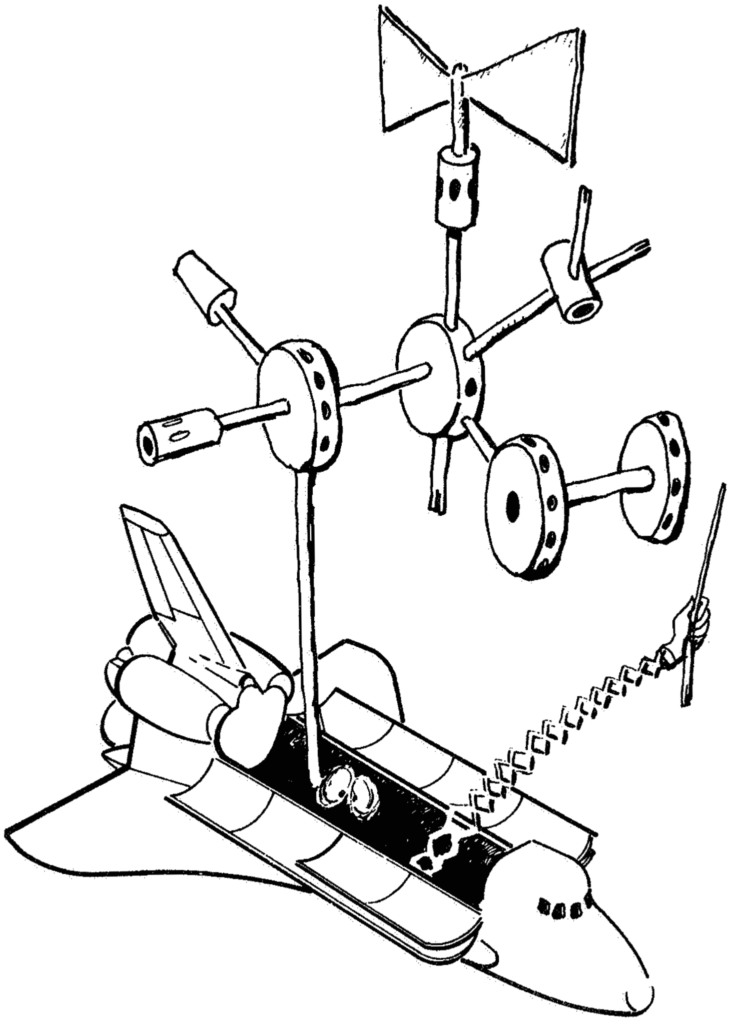
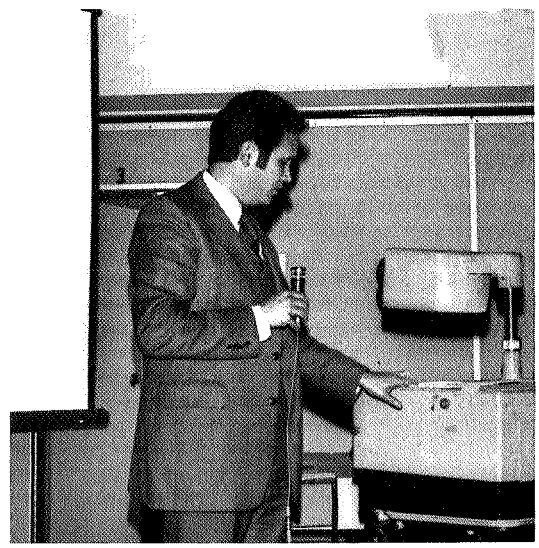
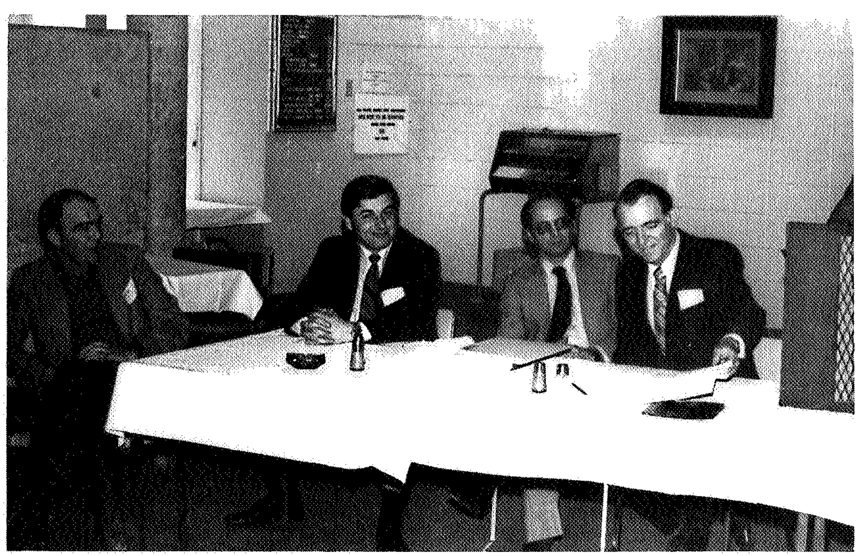


FIGURE 18, "TINKERTOY" PLATFORM.

SECTION V
DINNER PRESENTATION





A SUMMARY OF THE RESTON WORKSHOP ON THE ROLE OF ELECTRODYNAMICS OF THE MIDDLE ATMOSPHERE ON SOLAR TERRESTRIAL COUPLING

Arthur A. Few

Rice University

This proceedings has the purpose of sharing with the attendees of this workshop the proceedings of another similar workshop held one month ago in Reston, Virginia. The Reston Workshop on The Role of the Electrodynamics of the Middle Atmosphere on Solar Terrestrial Coupling was held January 17-19 at the Sheraton International Conference Center. Like this workshop the Reston workshop was held in a somewhat isolated environment and the participants were "captive." Like this workshop we were overworked (12-hour days) and overfed (banquets, dinners, lunches, etc.). Like this workshop the attendees represented a wide variety of disciplines and there were tutorial papers presented with the purpose of introducing pertinent review material to the workshop as a whole. The final program of the Reston Workshop is attached as Figure 1 to provide an outline of the presentations, some of which were excellent review papers.

Beyond the similarities noted above, the Reston Workshop and the one here at the University of Tennessee Space Institute were very different. The difference resulted from the two questions or problems addressed by the workshops. The question posed by The Reston Workshop was (paraphrasing): "What research needs to be done to understand the electrodynamics of the middle atmosphere?" This question is valid, important, and should be asked; but it is open-ended and divergent. The natural response of the participants was: We need to measure everything that we have always wanted to measure but could not measure before; and model everything.. .; and compare everything., .; etc.

In contrast, the question posed at this workshop is more focused and has a much higher probability of producing a focused recommendation. Again paraphrasing: "Can a satellite system designed to detect lightning radiations from space provide significantly useful information to a wide spectrum of users?" The way that this workshop is organized lends itself to providing a yes or no answer.

At The Reston Workshop the participants were divided into three groups, each with a chairman and recorders. I call your attention to the figure provided for the designations of the groups and leaders. The groups met individually for three sessions to produce recommendations complete with approach and rationale (see NASA **CP-2090).**

FIGURE 1

Final Program
Workshop on the Role of the Electrodynamics
of the Middle Atmosphere on Solar Terrestrial Coupling

January 17-19, 1979
Sheraton International Conference Center
Reston, Virginia

Wednesday,	January 17: Tutorial	
9:00	Conference Logistics	
9:05	Welcome Dr. Sigfried J. Bauer	Associate Director of Science Goddard Space Flight Center
9:10	Expectations Dr. David Cauffman	NASA Headquarters
Conference Theme		
9:25	The Dynamical Atmosphere Dr. George Reid	NOAA
10:30	Coffee	
The Middle Atmosphere		
10:45	Direct Energy Inputs Dr. T. J. Rosenberg Dr. L. J. Lanzerotti	University of Maryland Bell Laboratories
11:30	Ion Chemistry Dr. Eldon Ferguson	NOAA
12:15	Lunch	
1:15	$\bar{E}$, σ and $\bar{J}$ Dr. Ray Roble	NCAR
Lower Atmospheric Influences		
2:00	Tropospheric Effects on the Stratosphere and Vice-Versa Dr. Marvin Geller	University of Miami
2:35	Tropospheric Electrification Dr. Bernard Vonnegut	State University of New York
3:10	Coffee	
Upper Atmosphere Influences		
3:25	Energy and Mass Transport Dr. Hans Mayr	Goddard Space Flight Center
4:00	Electric Generators Dr. Gerald Atkinson	Communications Research Center Ottawa

4:35 Areas where Solar-Terrestrial Coupling may Influence the Middle Atmosphere
Dr. Richard Goldberg — Goddard Space Flight Center

5:15 Discussion

7:00 Dinner

9:00 Experimental Programs having Impact on the Middle Atmosphere
Dr. George Newton — NASA/Headquarters-Sciences
Dr. James Dodge — NASA/Headquarters-Applications
Dr. Herbert Carlson — NSF
Dr. James Hughes — ONR

Thursday, January 18: Workshops

9:00 Workshop Groups

A. Electrical Coupling through the Middle Atmosphere
Chairman: Dr. Chung Park — Stanford University
Reporters: Dr. Arthur Few — Rice University
Dr. Michael Kelley — Cornell University

B. Middle Atmosphere Conductivity and Currents
Chairman: Dr. Paul Hays — University of Michigan
Dr. Richard Goldberg — NASA/GSFC
Dr. Laurence Jones — University of Michigan
Dr. Les Smith — University of Illinois

C. Ion Composition, Chemistry, and Dynamics
Chairman: Dr. Rocco Narcisi — AFGL
Reporters: Dr. Janet Luhman — Aerospace Corp.
Dr. Volker Mohnen — State University of New York

12:15 Lunch

1:15 Workshop Groups

3:15 Coffee

3:30 Joint Session
Reporters' reports and discussinn

Friday, January 19: Workshops

9:00 Workshop Groups

12:00 Lunch

1:00 Joint Session
Chairmen's reports of recommendations

2:30 Coffee

2:45 Review Panel Discussion

Unfortunately the structure of the workshop did not lend itself to synthesizing the diverse "wants" of the participants into a realistic list of recommendations with priorities. At the conclusion of the workshop we had generated a very long "want" list, The list was well thought out with approach and rationale, but it contained a lot of redundancy.

Figure 2, labeled "The Output," enumerates the recommendations generated by the workshop groups; there are some fifty-three (53) of them compared to a total attendance of seventy-four (74) persons. In my opinion there will need to be an intense editing of the workshop's output before the resulting document will be useful to NASA.

I have listed in Figure 3 some recurring themes that were evident in the final joint session. This list is subjective and is not meant to replace a more objective editing of the workshop recommendations. From my recollection the list provides a fair and general statement of The Reston Workshop recommendations.

Postscript

At the time this report is going into the final editing stages, I have received a preprint of the final report of The Reston Workshop and would like to add the following comments and some additional figures. Dr. Nelson Maynard of NASA Goddard Space Flight Center has done a splendid job of editing and synthesizing the output of The Reston Workshop and has produced a very good working document on the needs for and the means of doing research on the electrodynamics of the middle atmosphere. I am including the table of contents (Figure 4) and a figure from that report (Figure 5) in this summary.

FIGURE 2

THE OUTPUT

GROUP A — ELECTRICAL COUPLING THROUGH THE MIDDLE ATMOSPHERE

11 PAGES CONTAINING:

8 RECOMMENDATIONS WITH APPROACH AND RATIONALE

2 ENDORSEMENTS (ONE WAS FOR THIS WORKSHOP)

GROUP B — MIDDLE ATMOSPHERE CONDUCTIVITY AND CURRENTS

7 PAGES:

SUB GROUP B-1	4 RECOMMENDATIONS (2 OF WHICH HAD 10 SPECIFIC MEASUREMENTS)
SUB GROUP B-2	4 RECOMMENDATIONS
SUB GROUP B-3	6 RECOMMENDATIONS

GROUP C — ION COMPOSITION, CHEMISTRY AND DYNAMICS

12 PAGES:

6 SUB GROUPS AND

21 RECOMMENDATIONS

TOTALS — 53 RECOMMENDATIONS

(TOTAL PRE-REGISTERED ATTENDANCE: 74 PERSONS)

FIGURE 3

RECURRING THEMES

1. NEED FOR MULTI-PROBE, MULTI-TECHNIQUE CAMPAIGN-TYPE EXPERIMENTS TO OBTAIN SIMULTANEOUS MEASUREMENTS OF MIDDLE ATMOSPHERE ELECTRICAL PARAMETERS.

2. NEED FOR INTERCALIBRATION OF MEASURING SYSTEMS: GROUND, REMOTE, BALLOON, ROCKET, DROPSONDE, SPACECRAFT.

3. NEED FOR ENHANCED MODELING CAPABILITY ALLOWING IMTERACTIONS AND FEEDBACK.

4. NEED TO DEVELOP A CLIMATOLOGY OF MIDDLE ATMOSPHERE ELECTRODYNAMICS.

FIGURE 4. TABLE OF CONTENTS FROM THE RESTON WORKSHOP FINAL REPORT.

Contents

FIGURE 4. (Continued)

MIDDLE ATMOSPHERE ELECTRODYNAMICS
(MAE)

1. MIDDLE ATMOSPHERE (MA) ELECTRODYNAMICAL PARAMETERS

Ionospheric (Upper) Boundary Conditions

What	Means*	Rec #
Magnetospheric electric field	DE,UARS,CRM	1.31
energetic charged particles	DE,S	1.32
solar radiation	UARS,S,B	1.33
galactic cosmic rays	S,B	1.34

Electrodynamics within the MA

What	Means*	Rec #
electric field+	R	1.11
pos. and neg. ion comp.+	R,B	1.121
neutral dynamics+	R,G	1.122
aerosols+	R,UARS	1.123

Tropospheric (Lower) Boundary Conditions

What	Means*	Rec #
fair weather electric field electric field currents conductivity	B,G,A	1.121
thunderstorm dynamics electric field ions and particulates currents conductivity	B,G,A	1.22

2. MODELS AND SUPPORTIVE LABORATORY MEASUREMENTS

What	Scope	Rec #
electrical models	global	2.1
electrical models	[illegible]	2.1
ion composition models	global	2.2
ion composition models	local chem.	2.2
lab verification of ion chemistry		2.3

3. PROBLEM ORIENTED RESEARCH IN MAE

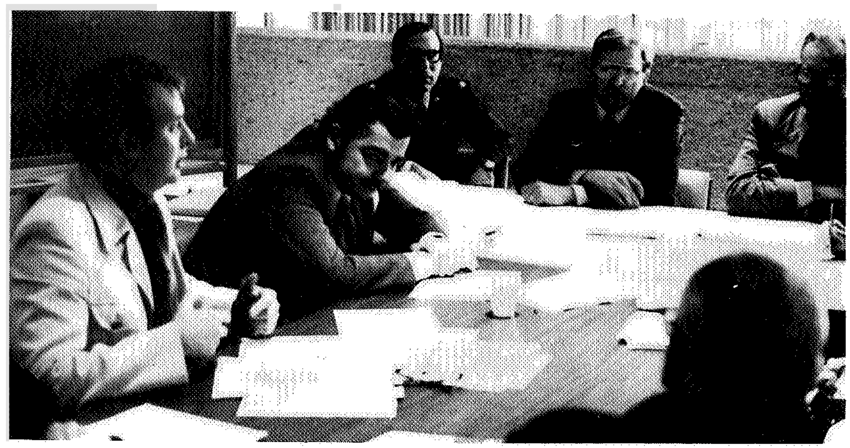
(coordinated research into the coupling between MAE and external influences).

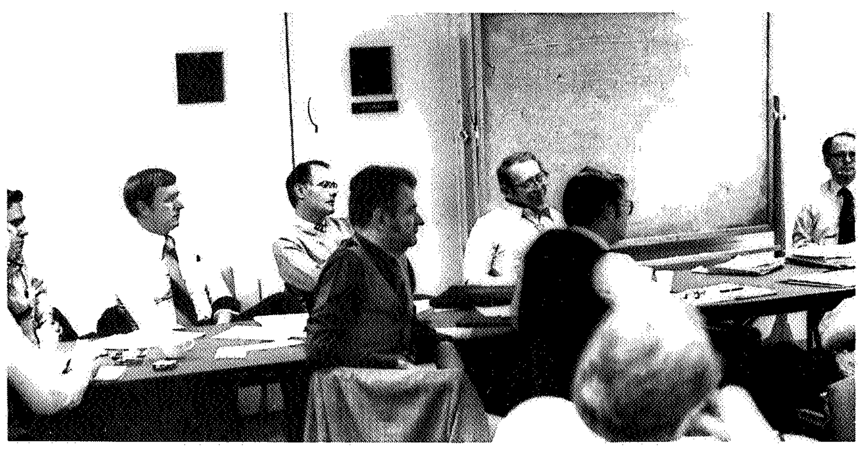
Subset of Problems	Rec #
electric field coupling during geomagnetic activity	3.1
solar effects on MAE	3.2
thunderstorm effects on MAE	3.3
global scale behavior on MAE	3.4

+new measurement techniques or significant improvements in techniques required
*R-sounding rocket, B-balloon, G-ground based, A-aircraft, S-satellite. Specific satellites: DE-Dynamics Explorer, UARS-Upper Atmosphere Research Satellite, CRM-Chemical Release Module.

FIGURE 5. EXCERPT FROM THE RESTON WORKSHOP FINAL REPORT

SECTION VI COMMITTEE REPORTS





ELECTROMAGNETIC TECHNIQUES COMMITTEE

Lothar H. Ruhnke
Naval Research Laboratory

The Electromagnetic Techniques Committee had some very helpful discussions and interactions with the other workshop committees. There were also lively discussions among the RF Committee participants. The principal participants were: Heinz Kasemir, Colutron Research; Thomas Shumpert and Martial Honnell, Auburn University; David Atlas and David LeVine, NASA Goddard Space Flight Center; James Harper, NASA Marshall Space Flight Center; Richard Johnson, Southwest Research Institute; and Bill Taylor, National Severe Storms Laboratory. This presentation of the committee report was guided along the five major points as outlined in the workshop description. Only two additional points were considered; namely, an overview of the general situation, which is presented as a brief introduction, and some conciuding recommendations for action. The viewgraphs used by the chairman in the presentation are given at the end of the report.

When one investigates RF techniques, one must consider a very wide range of frequencies, starting from the DC component of electric current which flows upward from a thunderstorm up to wavelengths appropriate for analysis by the Optics Committee. We considered frequencies into the infrared and discussed each frequency region separately to determine whether the region had potential for use and exactly what that potential might be.

There are limitations but also some possibilities when the DC component is considered. As Dr. Kasemir has shown, a limited region above each thunderstorm carries a vertical current of about 1 ampere towards the ionosphere. In the ionosphere, distortion and bending of this current takes place through the interaction with geomagnetic field. In situ sensing by current probes on satellites might reveal the location and intensity of thunderstorms. The limitations are most likely to be very low resolution. There is, however, a possibility that these currents might be indicative of the severity and location of thunderstorms. If information about the DC component has to be obtained, then it is recommended that low-altitude satellites be used, preferably located at about 100 kilometers altitude. There are, however, also some possibilities to use satellites between 100 and 200 kilometers. The most severe practical problem will most likely be the unknown technology and unknown science in this research area. At present, one does not know if indeed these currents do flow and, if so, what path they take. Ultimately the question of how these currents can be detected must also be answered. Also, very little is known about the background noise and what other currents might be present due to ionospheric events. Even considering these many problems, the possibility exists that one might be able to develop a very elegant system of monitoring thunderstorms on a global scale. The further possibility also exists that the developed tools can be used to study in situ relations between thunderstorms and solar events. This is an area which very much needs further research. Such research will enhance our understanding of the global circuit, and possibly by DC measurements of the currents with ionospheric and solar events produce a significant breakthrough in solar-weather controversy.

We next considered the electromagnetic frequency range up to 50 kHz (VLF). It is in this frequency range that the ionosphere is a good conductor and upward propagating lightning signals are highly attenuated. Also, receivers in this frequency band usually have poor spatial resolution. Noise problems might also be present. Very little is known about the propagation of radiation through the ionosphere in this frequency range and what problems due to background noise might exist. It appears that this frequency range is not very suitable.

The next frequency range under consideration is from 150 kHz to about 30 MHz (LF, MF HF). It is in this frequency range that the ionosphere behaves as a dielectric layer. Propagation characteristics are highly variable and unpredictable; therefore it is not anticipated that there will be applications for using this frequency range.

The situation changes drastically in the frequency range from 30 MHz to approximately 1 GHz. Useful measurements are probably possible in this range, even when some limitations are apparent. First, the background noise is unknown at geosynchronous satellite altitude and it is not clear which noise sources must be considered. For example, does the cosmic noise from outer space have any significance? The second problem is that the antennas must be very large structures in order to obtain good resolution. Limiting the time resolution might possibly reduce noise. But if one is constrained to average for some time, one might lose all signatures on the lightning signal and little knowledge of lightning characteristics would be obtained. In this frequency range, it looks feasible that one can obtain flash rate counting. It might also be possible to infer the stroke type and some other characteristics of the lightning. There is also a good possibility that such a system might be complementary to any signal which might be obtained by optical means. One major advantage is that a signal from the thunderstorm will not be attenuated to a great extent by the cloud particles or by precipitation.

When one considers the frequencies from 1 GHz to the infrared, one finds there is practically no knowledge about the lightning characteristics in this frequency range. This, of course, is a limitation at the present time. Also, the background noise which has to be considered is not known. It is probable that the thermal radiation from the earth's surface and oceans is a possible noise limiting factor. Propagation in this frequency range may be limited not only by the ionosphere but also by the amount of liquid water and water vapor in the path from the thunderstorm to the observation satellite. One must remember that a thunderstorm has a high liquid water content. In this particular frequency range there could be limitations also just because of the presence of water vapor in the communications path. The lightning signal coming from the clouds will not be affected by scattering and absorption on cloud particles as much as in the optical range. At these high frequencies, there will most likely be sufficient spatial resolution from a geosynchronous orbit. There is also the possibility that one might gain some insight into the lightning characteristics from line emissions in the far infrared and microwave frequency region.

Discussions were held with the user committees to determine their requirements. The RF Committee was able to compile what it felt was a priority list. Upon surveying all the inputs from the different individuals involved, it was decided that the number one priority was to extend our knowledge of the lightning frequency spectrum into the GHz range. It was pointed out that present knowledge concerning power levels is extremely insufficient and that a simple 1/F extension from the VLF is probably not sufficient to make a good judgment in the GHz frequency range. It was suggested that research be supported in this area. The second priority item was to investigate the background noise and to determine a signal-to-noise ratio, if possible. If measurements in outer space at these wavelengths are to be adequately taken, then problems concerning the signal-to-noise ratio are a critical issue and one which needs to be solved before further research and development are attempted. Lightning characteristics in the RF frequency range have to be correlated to optical lightning characteristics and related to those quantities which are needed by the users. This constitutes a major problem as far as user requirements are concerned. If one wants to use the signal from the DC currents, one needs a much better understanding of the global circuit theory. In particular, the influence of the magnetic field on conductivity is a significant area which needs research before one can proceed with further experiments.

The user committees have generally stated that they desire real-time information. Some, however, principally the Atmospheric Electricity and Meteorology Committee, were satisfied with statistical surveys and sporadic sampling. It appears that one must make some kind of compromise between real-time and sporadic sampling. The problem exists that most of the users want to look simultaneously at very large areas, which then is in conflict with their space resolution requirements. A trade-off will probably be most likely required. If counting were the only function to be performed, then good time resolution would not be necessary; however, if more information such as lightning characteristics is desired, then one would need good time resolution. The scientists involved will have to consider the trade-off between lower orbitals and synchronous orbit and what is possible and what is not possible using these two different types of satellites. At relatively low frequencies, signal-to-noise ratios will be more favorable; however, this interferes with the other aspect that one should use a high frequency to limit antenna size for spatial resolution. The above trade-offs are indeed difficult to solve in two and one-half days, and any decision-making will probably happen downstream.

A good number of the users need to know flash rate, stroke type and whether the lightning event is cloud-to-cloud or cloud-to-ground. It was also expressed that a knowledge of stroke rate, peak currents, rise time, waveform information and the severity of the storm would be beneficial. None of this information is directly available from RF information above the ionosphere. However, some type of inference modeling might be possible by using a hybrid RF and optical system. Preliminary information in the frequency ranges between 50 MHz and 100 GHz could probably be obtained from existing space platforms. For instance, instrumentation on other satellites could provide us with lightning signals from five or six different wavelengths in the microwave frequency region. There is also the possibility of obtaining information from the satellite pictures that are presently being taken. Of course, for any satellite system one needs to compare the information gathered with ground truth measurements to come to some assessment or estimate in terms of thunderstorm severity. One can then use an inference model to obtain a good relationship between ground truth and RF signature. If this were possible, one would perhaps be able to really understand what happens in a thunderstorm in terms of user requirements. The relationship between the RF signature and ground truth is one problem that has not been solved to date and must be considered as a further research need.

The committee next considered existing space technology and listed the satellites which presently have RF experiments. These experiments could possibly be used to answer some of the questions about the RF signals from lightning. In addition to background noise and signal-to-noise ratio technology, other space technology could be tested on aircraft. Microwave receiver systems which are presently used to measure brightness temperatures could be modified to some degree in order to enhance time resolution. Flash counting could be obtained, and if one were able to fly aircraft at high enough altitudes above thunderstorms, one might also obtain some firsthand data on the signature coming from lightning. U-2 type aircraft equipped with RF detection equipment over a wide range of frequencies could be readily used, Perhaps interactions with other government agencies could lead to the initiation of such a program.

The next point considered was the technology needs of the users. They need a high-resolution geostationary or orbital RF lightning detection system for global and regional measurements. This is quite a requirement, but as communicated to the Electromagnetic Techniques Committee, this is indeed their requirement.

Technology to meet the users' requirements was then discussed. What is needed to meet the users' requirements is to produce a system in the frequency range from 50 to 1,000 MHz, most likely a very large interferometer, either a time-rising or concave type, together with an adaptive scanner that can be used to scan areas which will most likely encounter thunderstorms. Scanning guidance could possibly be carried out by utilizing IR or cloud pictures from satellites. In order to deduce flash rate, peak current or rise time information, it will probably be necessary to have some kind of a smart filter. There is a definite need to complement the optical sensor. One needs also a system which can send as well as receive information. Multiple-feed, multiple-use technology would probably be best. The instrumentation, however, is very expensive, and large expenditures are probably involved. A hybrid multiple-use system is therefore recommended.

One of the next items considered is alternative solutions. There may indeed be other alternatives which are economically feasible. One such possibility is the use of a VLF ground system which would cover the United States with three or four units, perhaps not with the resolution or accuracy desired, but able to obtain a fairly good idea about the movement and severity of thunderstorms. One other alternative, of course, is to set up a network of lightning monitoring stations of the type developed by Krider and others. It would most probably require approximately $20,000,000 for a network of this kind; however, this kind of network may not be as cost-ineffective as it first appears. One might also have some type of hybrid system which uses the satellite as a data-gathering system instead of the data-gathering system being located on the ground. As an example, one could use a small, inexpensive probe to measure the electric field. This probe could be constructed so that corona would occur at a few kilovolts per meter on a sharp point which would trigger a small transmitter which could be detected from a satellite. The circuit could be built for a nominal price and distributed to a few thousand locations over the United States. The satellite could readily read out the electric field distribution on the ground. The last point that should be made is that when one considers the users' requirements as a whole, it must be realized that they are not achievable directly. However, this is also true for other users of space platforms; for instance, remote sensing users. Such things as wind velocity and direction or precipitation cannot be directly measured. What has been done is to infer these quantities from other measurements. In view of this, the requirements probably must be rephrased by the users in such a way that they can be easily satisfied. A further point is that the users should probably be happy with any usable information that they can obtain. This was demonstrated by the attitude of the Atmospheric Electricity and Meteorology Committee when they expressed the feeling that anything is better than nothing.

One needs, of course, some kind of recommendations for future research and recommendations for a plan of action. If an RF lightning system is to be developed, in what frequency range should it operate? The first priority, of course, is that one needs to know the power spectrum at high frequencies. It is recommended that measurements be extended from 50 MHz to 100 GHz. One would also like to obtain flash rate measurements from aircraft above thunderstorms in both optical and several RF and compare this to good ground truth data. The information should be in terms of what users need, i.e. peak current, wave shape, and perhaps location within the cloud, etc.

The second priority is that noise problems should be investigated. This could possibly be accomplished by existing satellites. These could be used to investigate both the signature and background noise. It appears that if one goes high enough in frequency, the only noise that will be present is the radiation from the earth's surface. This then would probably be the background noise level and would have to be recognized in the lightning signals.

The next priority would be an investigation into the needed time and space resolution relative to economic factors. Specifically, what size antenna could be tolerated with regard to the frequency choice or multiple-use choice? The type of scanning technique would also have to be considered. The next step would be to go to the user community and obtain their concensus concerning probable performance of the system. The first simple space experiment could then be designed. Next priority would be to consider the low frequency and DC range. At first, the distribution of thunderstorm currents at ionospheric altitudes should be analyzed and verified by experiment or modeling. Then one could design a space experiment to see if there is any truth to a thunderstorm detection concept sensing DC currents. These preparations, of course, would have to interact very strongly with other research endeavors in the global circuit area and with other research groups in order to be effective.

VIEWGRAPHS USED DURING THE PRESENTATION

(1)

FREQ.	LIMITATIONS	POSSIBILITIES
D.C.	LOW SPACE RESOLUTION LOW ALTITUDE SATELLITE UNKNOWN TECHNOLOGY	CURRENT DENSITY INDICATIVE OF STORM INTENSITY GLOBAL MONITORING OF THUNDER-STORM ACTIVITY RELATION TO SOLAR EVENTS UNDERSTANDING OF GLOBAL CIRCUIT
ELF, VLF	HIGHLY ABSORBING IONOSPHERE NO SPACF RESOLUTION NOISE PROBLEM	WHISTLER MODE DETECTION
MH, HF TO 30 MHz	HIGH REFRACTIVE INDEX OF IONOSPHERE (MIRROR BEHAVIOR)	USED TO ADVANTAGE BY JAPANESE SATELLITE - IRIS EFFECT
30 MHz TO 1000 MHz	BACKGROUND NOISE ANTENNA SIZE SPACE AND TIME RESOLUTION LOW KNOWLEDGE OF LIGHTNING CHARACTERISTICS	FLASH RATE COUNTING INFERENCE TO STROKE TYPE AND PEAK CURRENT COMPLEMENTARY TO OPTICAL SIGNAL NO SCATTER ATTENUATION BY CLOUDS AND PRECIPITATION SUFFICIENT RESOLUTION FROM LOW ORBIT SATELLITE
1 GHz TO IR	ALMOST NO KNOWLEDGE OF LIGHTNING CHARACTER1STICS NOISE FROM THERMAL BRIGHT-NESS TEMP. OF SURFACE WATER VAPOR LIMITED PROPAGATION	LIGHTNING SIGNAL PENETRATES CLOUDS SUFFICIENT RESOLUTION FROM SYNCHRONOUS ORBIT ADDITIONAL LIGHTNING INFORMA-TION FROM LINE EMISSIONS

PROBLEM PRIORITIES

(2)

EXTENSION OF LIGHTNING POWER SPECTRUM FROM 100 MHz to 100 GHz

BACKGROUND NOISE AND SIGNAL-TO-NOISE RATIOS

TRADE-OFF DILEMMA

INFERENCE OF LIGHTNING CHARACTERISTICS FROM RF SIGNATURE

GLOBAL CIRCUIT THEORY

TRADE-OFF DILEMMA (3)

REAL TIME - SPORADIC SAMPLING

SIMULTANEOUS LARGE AREA COVERAGE

SPACE RESOLUTION

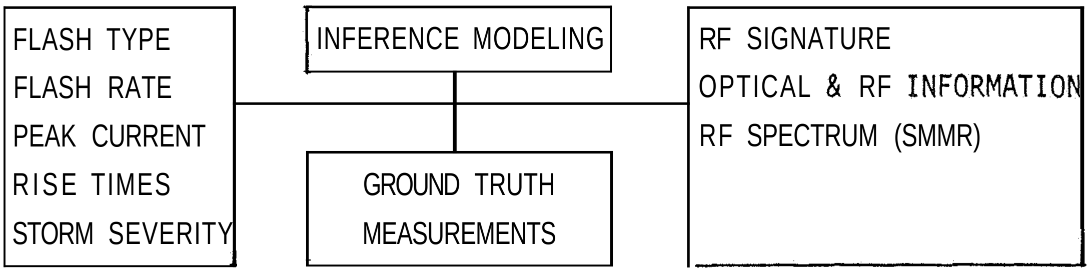
TIME RESOLUTION

LOW ORBIT - SYNCHRONOUS ORBIT

LOW FREQUENCY FOR HIGH SIGNAL AMPLITUDE (30 MHz)

HIGH FREQUENCY FOR SMALL ANTENNA SIZE (30 GHz)

(4)



EXISTING SPACE TECHNOLOGY (5)

ISS 1/2	SMMR TYPE EQUIPMENT ON NASA AIRCRAFT
SCATTER	CIA TYPE U2
ATS 6	
ARIEL - III	
RAE - I	
VELA - 4B	

TECHNOLOGY NEEDS TO MEET USER REQUIREMENTS (6)

A HIGH RESOLUTION (SPACE-TIME) GEOSTATIONARY AND/OR ORBITAL RF LIGHTNING DETECTION SYSTEM FOR GLOBAL AND REGIONAL MEASUREMENTS.

TECHNOLOGY ANSWER TO MEET USER REQUIREMENTS (7)

100 TO 1000 MHz SYSTEM

LARGE INTERFEROMETER (PHASE OR TIME-OF-ARRIVAL)

ADAPTIVE SCANNER (GUIDED BY IR CLOUD DETECTOR)

SMART FILTERS (TO DEDUCE FLASH RATE, PEAK CURRENT AND RISE TIMES)

COMPLEMENTED BY OPTICAL SENSOR

MULTIPLE BEAM TECHNOLOGY

PHASE ARRAY

MULTIPLE USE

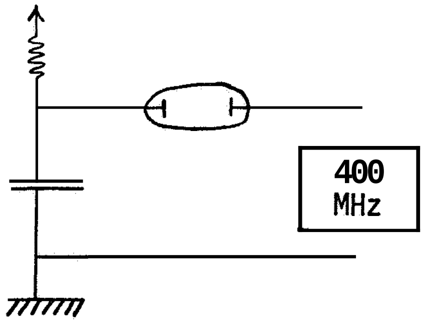
ALTERNATIVE SOLUTIONS (8)

GROUND-BASED VLF SYSTEMS (VOLLAND-HEYDT)

MASSIVE DISTRIBUTION OF LOCAL STATIONS (KRIDER, ETC.)

SATELLITE USE OF DATA COLLECTION PLATFORM

ECONOMIC ELECTRIC FIELD SENSOR FOR SATELLITE INTERROGATION SYSTEM (9)



CONCLUSIONS (10)

USER REQUIREMENTS ARE GENERALLY UNREALISTIC

USERS SHOULD APPRECIATE ANY SATELLITE-DERIVED RESULTS

RECOMMENDATION FOR PLAN OF ACTION (RF LIGHTNING SCANNER) (11)

- INVESTIGATE LIGHTNING SIGNATURES FROM 100 MHz to 100 GHz

  RELATE A/C MEASUREMENTS TO OPTICAL SIGNATURES AND TO GROUND TRUTH DATA ON PEAK CURRENTS, WAVE SHAPE (VLF) AND LOCATION WITHIN CLOUDS

- INVESTIGATE NOISE PROBLEMS OF RECEIVERS IN SYNCHRONOUS ORBITS

- INVESTIGATE RESOLUTION - VERSUS - ECONOMY PROBLEMS

  (SIZE, FREQUENCY, MULTIPLE USE, SCANNING TECHNIQUES)

- COMPROMISE USER REQUIREMENTS WITHIN TRADE-OFF DILEMMA AND DESIGN FIRST SPACE EQUIPMENT

RECOMMENDATION FOR PLAN OF ACTION (GLOBAL CIRCUIT SCANNER) (12)

ANALYZE DISTRIBUTION OF THUNDERSTORM CURRENTS AT 100 KM TO 200 KM ALTITUDE.

PREPARE EXPERIMENT TO VERIFY THEORY AND THUNDERSTORM DETECTION CONCEPT.

INTERACT WITH SOLAR-WEATHER RESEARCH, MAP, AERONOMY AND IONOSPHERIC PHYSICS.

OPTICAL TECHNIQUES COMMITTEE

Richard E. Orville
State University of New York at Albany

The discussions and deliberations of the last few days were dependent upon the fine individuals who participated in the committee. The Optical Techniques Committee was actually a combination of two types of individuals: those who have carried out field observations but have no experience in satellite design and those who have carried out the design of satellites without field experience in the study of lightning. The principal participants were: Don Blue, Georgia Tech; Marx Brook, New Mexico Institute of Mining and Technology; Thomas Barnes, Earl Reinbolt and Dale Craig, NASA Marshall Space Flight Center; Bruce Edgar, Aerospace Corporation; Gary Mauth and Richard Spalding, Sandia Laboratories; William Wolf, University of Arizona; Greg Sanger, Lawrence Livermore Lab; and William Wetherell, ITEK Corporation. It was with these capable personnel that the summary comments were compiled. The viewgraphs used by the chairman in the presentation are given at the end of the report.

It should be kept in mind that the lightning sensor systems which have been discussed will be only a part of the overall observing system. There will be other observation platforms in space which will be looking at other aspects of the earth's atmosphere such as clouds, convection cells and moisture content. The monitoring of lightning activity will be in addition to these other observations. Together, the total number of observations will comprise an important meso-meteorological data set. It was thought that it would therefore be most helpful in reaching any conclusions if the total picture and total number of measurements were kept in mind.

The committee put together an outline of the various capabilities and user requirements. The outline was very helpful in defining what can or cannot be done using optical techniques. The committee addressed the questions posed to us by the Workshop Organizing Committee and felt it was reasonable to proceed on the suggested items; for example, the first question of identifying, in order of importance, the most pressing problems within the context of the committee's title. It is difficult to determine which of the problems is most important; however, it was decided that the measurement of intercloud and cloud-to-ground flashes and their discrimination is the highest priority. As far as the relation of radiation to current, it is our opinion that the capability does not exist to determine the current characteristics from the radiation signature. Simultaneous measurements of the optical radiation and current have been made, but it is not obvious that a unique relationship exists. As far as making observations of the lightning spectrum is concerned, the intercloud spectrum is still largely an unknown. However, some progress is being made on this problem. Spectra of cloud-to-ground flashes have been obtained from ground stations; however, to the committee's knowledge, no spectral observations from above the clouds have been obtained to date. At present, a good deal of information is available about lightning spectra between clouds and ground, but the question remaining is what the spectrum will look like from above the cloud. That information has not yet been determined. There are probably going to be some serious problems separating the lightning signal from the background noise.

The second question to be considered was the identity of the technology needs to meet the users' requirements. Basically, more quantitative information is needed to assist in designing the systems to meet the requirements of the users. One needs reasonable conceptual instrument designs. This, of course, could not be done in this workshop. It is most likely going to be accomplished by design engineers meeting after this workshop has been completed. It is hoped that they will be able to come up with several reasonable design systems. Certainly it is recognized that one is going to need on-board, very high-speed data processing. One is also going to need detector arrays with very high time resolution. There is also a need for large-fikld-of-view, 1ightweight optical systems.

The next consideration was to report on what current technology could be used to adequately instrument the satellite for observation of lightning characteristics. A resolution of four kilometers with a field of view of a few hundred kilometers seems reasonable. Current technology for sensitivities of 10^9 watts for local measurements is available. There has been some discussion about going below that, and a number of individuals agreed that by going to larger arrays, say 4,000 elements, it would be possible to raise the sensitivity to the order of 10^7 watts. It is recognized, of course, that the time resolution will be obtained at the expense of the sensitivity. Here one really has trade-offs. It is possible at this time with present technology to isolate the signal to look at certain regions. Whether it is to look at two, three, or four regions or whether it is to look at a few lines in a few regions is something to be determined in the future. It is agreed that the present platform pointing accuracy is adequate.

The next area for discussion is the alternate solutions for user problems. As far as alternate solutions for user problems, it is agreed that it will be extremely important to combine the optical measurements with other observations for the discrimination of intercloud and cloud-to-ground flashes. The committee has indicated to the user groups that there certainly is some possibility of separating the intracloud and cloud-to-ground discharges. However, there are some unknowns, and the Electromagnetic Techniques Committee seems to be of the same general opinion. Perhaps by combining the optical and RF observations one can remove these unknowns. Certainly more than one system can be used, and it also might be possible to have many nonsynchronous satellites. It is felt that geosynchronous would be the best, but an alternate solution would certainly be to have many nonsynchronous satellites. Of course, one could have ground systems which would work over the continental United States; however, there is no satisfactory ground network over the oceans at this time.

The question usually arises as to why one needs a committee *to* provide an adequate definition of requirements. The presentations and discussions with other groups can be and have been a big help to the Optical Techniques Committee, and it is recognized that there will have to be some give and take on each side. Ultimately one is going to have to say what is possible and what is not and what is the best solution to meet the needs of the majority of individuals involved. One final note is that a good deal of pioneering work in this area has been done by Bob Turman, who is intimately familiar with optical systems on satellites, and his experience should be very helpful in determining the ultimate optical sensors and equipment which can be used to measure lightning characteristics from space.

Recommendation for Plan of Action

It was agreed by our committee that the technology exists for building a lightning satellite detection system but that we need more numbers for the characteristics of lightning as seen from space. The following outline is a systematic plan to obtain this information.

A. Ground-based observations and studies

1. What are the spectral characteristics of the [illegible] lightning flash

2. Can lightning be detected against daylight background conditions?

3. What is a reasonable conceptual instrument design for an optical detection system?

B. High-altitude flights (U2)

1. Can lightning be detected from above clouds in the daytime?

2. How much energy in the optical region propagates through a cloud?

3. What percentage of lightning which occurs is actually detected? (i.e., ground truth)

C. Orbital flights (Shuttle)

1. What are the spectral characteristics of lightning as observed from space?

2. Can we distinguish between intracloud and cloud-to-ground lightning?

3. What percentage of lightning which occurs in the field of view is detected?

D. Satellite design considerations

1. What spatial resolution can be achieved?

2. What is the maximum sensitivity that can be obtained consistent with the desired spatial resolution?

3. What is the most appropriate time resolution?

3

VIEWGRAPHS USED DURING THE PRESENTATION

LIGHTNING SENSOR SYSTEM (1)

PART OF AN OBSERVATIONAL SYSTEM DETECTING

1. TALL STORMS
2. WIND SHEAR
3. RAPID VERTICAL DEVELOPMENT
4. PENETRATING CONVECTIVE CELLS
5. MOISTURE INFLUX

ALL ARE IMPORTANT TO MESOSCALE METEOROLOGICAL STUDIES.

(2)

	GEOG. AREA	DIURNAL INFOR.	EVENT RATE	CURRENT WAVEFORMS	STORM SIZE	IC/CG
UTILITIES	USA	Y	Y	Y	Y	Y
TELECOMM.	USA	N	Y	Y	Y	Y
FORECASTING	USA	Y	Y	N	Y	Y
USAF	GLOBAL	Y	Y	Y	Y	Y
		ETC,. .				

a

OPTICAL TECHNIQUES (3)

1. PRESSING PROBLEMS WITHIN CONTEXT OF COMMITTEE'S TITLE

   A. IC VS. CG FLASHES (OPTICAL SIGNATURE): CAN WE DISCRIMINATE BETWEEN THEM?

   B. RADIATION VS. CURRENT: DOES ANY RELATION EXIST?

   C. SPECTRA: WHAT ARE THE CHARACTERISTICS OF

      (1) IC FLASHES?

      (2) CG AND IC FLASHES OBSERVED FROM ABOVE CLOUDS?

   D. BACKGROUND CHARACTERISTICS: WHAT IS THE SIGNAL-TO-NOISE RATIO?

   E. NEED MORE "NUMBERS"; e.g., HOW MUCH ENERGY IS RADIATED BY LIGHTNING AS A FUNCTION OF WAVELENGTH AND HOW MUCH CAN BE EXPECTED TO REACH A SATELLITE?

2. TECHNICAL NEEDS TO MEET REQUIREMENTS OF THE USERS

   A. REASONABLE CONCEPTUAL INSTRUMENT DESIGNS

   B. ON-BOARD HIGH SPEED DATA PROCESSING

   C. DETECTOR ARRAYS AND TIME RESOLUTION

   D. LARGE APERTURE, LARGE FIELD OF VIEW, LIGHTWEIGHT OPTICS

3. CURRENT TECHNOLOGY IN SPACE PLATFORM SENSORS AVAILABLE FOR THE SOLUTION OF USER PROBLEMS (4)

   A. RESOLUTION OF 4 KM (1-4 KM FOR 200 x 200 KM COVERAGE)

   B. SENSITIVITY OF 10^9 WATTS FOR GLOBAL MEASUREMENTS (10^7 WATTS WITH 1 M APERTURE AND 4000 ELEMENTS) - TIME RESOLUTION WILL BE OBTAINED AT EXPENSE OF SENSITIVITY

   C. CAN SPECTRALLY ISOLATE THE SIGNAL

   D. PLATFORM POINTING ACCURACY IS ADEQUATE

4. ALTERNATE SOLUTIONS FOR USER PROBLEMS (5)

   A. OPTICAL AND EM OBSERVATIONS FOR IC VS. CG DISCRIMINATION

   B. MORE THAN ONE SYSTEM COULD BE USED; MANY NONSYNCHRONOUS SATELLITES COULD ALSO BE USED.

   C. GROUND SYSTEMS

5. HAVE USER COMMITTEES PROVIDED ADEQUATE DEFINITION OF REOUIREMENTS? COORDINATION NEEDED AMONG USERS (ROOM FOR "GIVE AND TAKE"?)

OPERATIONAL APPLICATIONS COMMITTEE

Rodney B. Bent
Atlantic Science Corporation

The Operational Applications Committee could not have been better, The group here was outstanding, and extremely good discussions were a result of the fine people in attendance. The principal participants were: Philip Corn, U.S. Air Force; Robert Frech, Florida Power and Light Company; Craig Chandler, U.S. Forest Service; Robert Nelson, Telephone Engineering, Inc.; David Rust, National Severe Storms Lab; Fred Sakate, Federal Aviation Administration; Joe Schaefer, National Severe Storms Forecast Center; Andy Weinheimer, Rice University; and Oley Wanaselja. It is hoped that with the interaction of all those in attendance the information contained in this report will not be biased in any way. The Operational Applications Committee considered many different users--the utilities, the FAA, the forestry people, the forecasting community, etc.--and were able to determine each of their requirements. It was, however, impossible to come up with one approach which would satisfy the requirements of all the users, Each user has his own requirements and expressed the belief that if they were not able to obtain these requirements from space observations they would be constrained to do the best they can with ground- and air-based measurements. The viewgraphs used by the chairman in the presentation are given at the end of the report.

Utility Requirements. Real-time information is needed to assist in planning the geographical areas in which repair crews are needed to be on duty. Careful planning based on accurate storm locations will save considerable funds normally spent by calling out crews unnecessarily. Knowledge of storm movement may also facilitate advance planning of load sharing on the grid system. Further work is needed in understanding the damage caused to distribution systems parts such as transformers. A better understanding of lightning wave shapes and events will also enhance modeling approaches used in the design of surge protection equipment. The requirements for the utilities in real time would be an accuracy goal of ±3 miles with a 15-mile tolerable limit.

FAA Requirements. The FAA requires very accurate real-time location of lightning. The National Transportation Safety Board has recommended that the FAA expedite installation of equipment to monitor thunderstorms within five nautical miles of the end of all active runways. This requirement is for the safety of the low-altitude aircraft on approach and take-off where mature thunderstorm gust front and lightning dangers are very real. The necessity for high accuracy of storm positions is obvious, and updates must be performed frequently and the data made available to over 250 control towers. Similar information will be required at Flight Service Stations, some of whose staff are to be replaced by automatic detection equipment. These service stations exist at local airports, of which there may be on the order of one thousand. For en route traffic, information provided by the 20 Air Traffic Control Centers should provide storm location with an accuracy of five miles. These facilities also need local warning information for auxiliary power start-up when thunderstorms are in the area.

Telecommunications Requirements. Real-time information is not necessary for these users, but further information is required on lightning statistics in order for there to be a better understanding of induced and direct surges produced by lightning in the communication networks. Protection of the electronic equipment at the end of these lines is extremely important as more and more modern fast-acting, solid-state equipment is being installed. This equipment is susceptible to rapid rise time surges.

Better information on storm size and storm days would allow protection statistics to be generated. The available isokeraunic maps are poor and considerably underestimate thunderstorms in some areas. Based on these inadequate statistics, equipment is at times purchased without adequate surge protection. A knowledge of intra-cloud as well as cloud-to-ground discharge characteristics is required because when these are over and parallel to lines, surges could develop up to 10 kV per km length of wire.

Forecasting Requirements. At present, storm forecasting relies on information from scores of radar sites around the country and their staff's ability to interpret weather radar data. The real-time requirements are directed to John Q. Public. It is suggested that 15-minute updates be required to an accuracy of ±2 miles. The necessity for accurate information was emphasized with a failure rate of only 10% in the proposed storm information. A strong proposal was put forward to the Sensor Committees to consider any means likely to provide information on severe storms. Certain forecasting centers are also replacing staff by automatic equipment, and these could benefit from satellite storm information. Further information is required to enhance the statistical data base on storm size, severity and the number of intra-cloud or cloud-to-ground discharges.

Forestry Requirements. Land management agencies need localized lightning information in order to pre-position crews in areas where concentrations of lightning-caused fires are probable and to direct fire detection aircraft to those same areas. Ideally, the forestry community would like to locate the position of 90% of all long-continuing current ground strikes within 250 meters in real time. With this ability, suppression crews could immediately and automatically be dispatched to probable fires. Short of this capability, the ability to track individual storms with a spatial resolution of two to five miles and a failure rate of not more than 10% would enable the agencies to substitute satellite tracking for their existing visual and land-based lightning location systems. One must also consider the forest service spatial resolution requirement of two to five miles for storm tracking at high altitudes. Maybe the cosine effect would be significant for the Alaska region. From a research standpoint, the ability to discriminate between dry and wet storms appears to be a logical satellite mission.

U.S. Air Force Requirements. The Air Weather Service is already instructing aircraft to fly no closer to a thunderstorm than 20 nautical miles; Their zone of interest is worldwide and their requirements are just as severe as the FAA's. It was also pointed out that the refueling of aircraft on the ground or in the air is dangerous during lightning conditions. Furthermore, the more sophisticated computerized equipment carried on military aircraft is potentially susceptible to transients caused by induced voltages in the craft's wiring. These transients appear to be principally coupled in the 1-20 MHz frequency range. Evidence from pilots flying sophisticated aircraft has indicated that transients induced in systems from nearby lightning have caused bomb doors to open and wing folding motors to activate.

For research purposes more information is needed on rise times and stroke current values as well as characteristics of intra-cloud and cloud-to-ground lightning.

Miscellaneous Requirements. It is believed that a real-time requirement for storm location to better than five miles is required by the Bureau of Mines in order to prevent premature detonation of explosives due to line surges. The U.S. Coast Guard also has suggested that the United States isokeraunic map be improved so that they may better plan for protecting the LORAN Systems. They have suffered many problems in new systems, as well as in old ones that are being updated with modern solid-state equipment. Ammunition manufacturing and storage facilities also need real-time lightning storm information.

Display Requirements. The real-time users indicated that a graphics display terminal is necessary to show immediate storm information. The terminal should show storm position, intensity, speed and direction of movement over a limited area of perhaps a 50-mile radius. The terminal users should have the capability of zeroing in on any grid area in the United States. In order for this to be achieved, a central computing facility should exist that is in direct communication with the satellite. This facility could furnish the software necessary for storm information, and low-based and land lines could pass the data to the remote terminals, costing only a few thousand dollars.

Satellite Orbit. Because around-the-clock information is required, a geostationary satellite or several orbiting satellites would probably be needed for continental United States mapping.

Summary of Discussions. The committee could not approve a single specifications requirement due to the varying needs of all the users. In fact, if the storm information from a satellite sensor system did not fall within the requirements of the FAA, they would do the best they could to provide their own ground-based system. A similar voice was heard from the forestry service. The second major issue was cost. Unless the satellite approach were cost effective, the users would continue to pursue ground monitoring approaches. One must take note that perhaps a ground-based system would provide all the information on storm location required by, say, a power utility in Florida over a statewide network. The system might then be programed to provide all the definite requirements at a cost probably similar to that required to connect to a satellite system. A ground network could also provide historical data on stroke characteristics. One basic question is, however, whether a utility would do their own research on this data to obtain the required storm information to improve the utility system modeling they require.

Meanwhile, the Bureau of Land Management and the FAA are pursuing their goal of providing the ground networks to meet their requirements. These goals will be achieved by the forestry service within five years when full coverage of the Bureau of Land Management's systems will be finalized and data made available to 300-500 locations. The upkeep of such a system is expensive, and costs are likely to be on the order of $200,000-$300,000 per year. Should a cost-effective satellite system be implemented, the forestry service would probably make full use of it.

The FAA's approach will probably be to proceed with the ground location system now under contract. This system provides a video display of storm positions, intensity and movement. Waveform rise times and peak values are also monitored for their future research in surge protection. It is unlikely that the FAA will make large-scale commitments within the next three to four years.

The U.S. Air Force will probably also proceed on an expensive course of setting up ground systems. Should a cost-effective satellite monitoring system become available, the Air Weather Service would no doubt pursue that line.

The communications people would probably prefer to spend their dollars on monitoring line surge characteristics instead of monitoring the lightning waveform. If a satellite monitoring system were made available, however, they would no doubt use it.

The forecasting area is vitally in need of improved storm data and will no doubt make full use of any satellite information provided. A need for pre-lightning cloud monitoring exists, but it is thought that without some real-time cloud turret buildup monitoring, the information would be difficult to obtain.

Summary of Discussions on Research-Related Parameters. It was agreed that most of the information reauested could be obtained from ground located experiments, but the importance of satellite monitoring was appreciated in terms of the large data base it would provide. There appears to be a definite need to update the isokeraunic maps to provide fine detail and to indicate lightning pockets. Obviously, long-term monitoring is necessary to get this type of information. It appears that the maps are currently being used extensively by many different facilities. A further requirement of correlation between lightning and intense precipitation was mentioned by both the forecasting group and the forestry service.

Interaction with the Optical Group. After the presentation of individual requirements, it was the opinion of the committee that storm location to ±2 miles was a definite probability. Some concern was expressed over the low failure-to-detect rates proposed by the users, and this warrants further study.

It is probably unlikely that optical signatures alone will be useful in locating possible severe storms (tornados), but there is a definite chance that return stroke signatures and ever-continuing current lightning can be detected by their spectral response. Optical signatures would not provide information on current rise times and magnitudes. The required accuracies could probably be provided from geosynchronous satellite distances, thus providing complete continental United States monitoring.

Interaction with the RF Group. One of the major problems of RF monitoring from space is obviously the elimination of information below about 30 MHz due to ionospheric effects. Highly directional antennas are also needed in order to lessen galactic noise as well as provide positional information.

It was obvious that much research still needs to be done. Restraints on temporal and spatial coverage seem to imply a geostationary satellite will be needed. At such distances the probability of meeting the spatial requirements is slim. The value of RF monitoring was, however, appreciated as this may be the only way to obtain the information, other than positioning, that is being requested by the committee. This information would contain rise time and peak amplitude data. A joint optical/RF monitoring scheme looks to be the most promising for providing the requirements of the operational users.

VIEWGRAPHS USED DURING THE PRESENTATION

(1)

Real Time

USER	GEOGRAPHIC AREA	SPATIAL RESOLUTION		SPATIAL RESOLUTION		EVENT/RATE OR INTENSITY	DIRECTION	SPEED	CLOUD/GROUND OR INNER CLOUD DISCRIMINATION	FALSE ALARM	FAIL TO DETECT
		GOAL	MAX	GOAL	MAX						
Utilities	CONUS	±2 mi	±5 mi	10 min	20 min	Yes	Yes	Yes	No	30%	30%
FAA	CONUS	±3 mi	5 mi	20 sec	1 min in terminal area--- 5 min on route	Yes	5-10°	±2 m/sec	No	30%	5%
Telecommunications	None										
Forecasting	CONUS	±2 mi	±15 mi	15 min	60 min	Yes	5-10°	±2.5 m/sec	Yes	30%	10%
Forest Service Fire Detection	CONUS	250 m	1 km	3 min	20 min	Yes	Yes	Yes	Yes, with continuing current monitor	10%	10%
Forest Service Storm Tracking	Western USA	±2 mi	±5 mi	15 min	45 min	Desirable	--	--	--	30%	10%
US Air Force (Best Estimate)	Worldwide	±3 mi	5 mi	5 min	10 min	Yes	5-10°	±2.5 m/sec	No	30%	10%

Research Information

USER	GEOGRAPHIC AREA	DIURNAL INFORMATION	EVENT RATE	CURRENT WAVEFORMS RISE & FALL TIME & PEAK MAGNITUDE	STORM SIZE	STROKES/ FLASH	SEVERE STORM MONITORING	RATIO OF INNER CLOUD TO GROUND DISCHARGES	RELATIONSHIP BETWEEN LIGHTNING & RAIN
Utilities	CONUS	Yes	Yes	Yes	Yes	Yes	No	Yes	No
Telecommunications	CONUS	No	Yes	Yes	Yes	Yes	No	Yes	No
Forecasting	CONUS	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
US Air Force	Worldwide	Yes	Yes	Yes	Yes	Yes	No	Yes	No
FAA	CONUS	No	No	Yes	No	Yes	No	Yes	No
Forestry Service	CONUS	No	No	No	No	No	No	No	Yes

ENGINEERING AI I'LICAT S COMMITTEE

E , 1 R. Whitehead*
University of Col ado

Thanks should initially go the fine comnittee which served so diligently in the last two and one-half days. A special thanks should go to Dale Vance, who was a very efficient recorder. The principal participants were: Dale Vance, Office of Scientific Systems and Development; Charles Ballentine, Tennessee Valley Authority; Edward Cohen, Rural Electrification Program; Arthur Few, Rice University; John Henz, Geophysical Research and Development Corporation; Larry Levey, Bel1 Laboratories; Donald Reynolds, IBM Corporation; Franklin Smith, Corps of Engineers; Art Westrom, Kearney National ; and John Birken, NAVAIR. The applications were considered in accordance with their priority and principally from the standpoint of final design considerations as distinct from operational considerations. Virtually all of the considerations expressed by the Operational Applications Committee are compatible with the needs of the Engineering Applications Committee. As a result, the remarks presented today will be limited to a great extent. The viewgraphs used by the chairman in the presentation are given at the end of the report.

The first priority is the problem of geographical distribution of ground and intra-cloud flash density. Until recently the scientific community has not been able to adequately measure ground flash density. There are over the earth a number of different types of ground counters; however, the information which has been collected over a period of 10-15 years has not been that reliable. Much better results are currently being obtained from present systems; however, supplementary information from a satellite program would be beneficial. At any rate, the geographical distribution of ground flash density is our first priority.

The second priority is the problem of lightning characteristics; i.e., current rate of rise, peak current, duration of stroke, duration of flash, number of strokes per flash, amplitude and duration of continuing current. The scientific community has at this time a great deal of this information available, but not at the accuracy required. In view of this, additional information is needed.

The third priority is the geographical distribution of total lightning activity and associated storm size and duration.

*Substituting for John D. Robb, Lightning and Transients Research Institute

The fourth priority is a continuous monitoring on a global scale. This was principally motivated by the desire to be of service to other nations, rather than to satisfy our own needs. At any rate, it would be beneficial if this type of information were available.

Our last priority is real-time monitoring. In this regard, it was felt that some of the committee guidelines simply did not apply to our task; for instance, the subject of geographical distribution of ground flash density. The potential for observations of space concerned with global coverage, consistency of data, removal of and consolidated data available through a simplified system is not possible using space observations alone. It was also believed that lightning characteristics would be difficult to obtain from space observations alone. Some kind of real-time monitoring could be simplified and coordinated through the use of a space observational system.

A composite map derived from the isokeraunic level and the distribution of the earth's resistivity was also considered. A combination of these two facts leads to the cross-sectional areas of very high probability of lightning damage, the areas of higher-than-average probability, and other areas which are lower than the average. This map is presented as part of our committee report to indicate the type of things that this committee would hope to come out of the composite studies and the suggestions made here and hopefully will help in the allocation of resources to areas which will pay off with the greatest dividends. This map and the report in which it is contained are available from Edward Cohen, Rural Electrification Administration. It is, however, in rough draft form, and significant changes are likely to be made.

VIEWGRAPHS USED DURING THE PRESENTATION

USER COMMITTEE (ENGINEERING APPLICATIONS) (1)

From your interactions with other committees, identify in order of decreasing importance* the most pressing problems within the context of your committee's title. (*May differ according to objectives.)

Priority	Problem
A.	Geographical distribution of total flash density separated into (a) Ground flash density component (b) Intracloud flash component
B.	Lightning characteristics** (**By frequency distributions if possible. Order of listing will vary with nature of problem.) (a) Maximum rate of rise of current $(di/dt)_{max}$ (b) Peak current (amplitude) i_{max} (c) Duration of strokes (components of flash) (d) Duration of flash (e) Strokes per flash (f) Coulombs per flash (g) Coulombs per stroke (h) Time intervals between strokes (i) Amplitude and duration of continuing current
C.	Geographical distribution of total lightning activity (Storm size and duration)
D.	Continuous monitoring on a global scale
E.	Real-time monitoring

State the physical variables required for the solution of each problem. (2)

Problem	Variables
A.	Intracloud and ground flashes per square kilometer* per unit of time. The unit of time should be (*4 km x 4 km grid resolution sufficient.) (a) Year (b) Month (c) Day (?) (d) Hourly flash density by months
B.	Self-evident. See Viewgraph 1, Priority B.
C.	As in A above plus statistical data on rate by sensor cell and rate by contiguously-active sensor cell in the same storm system. Five minute resolution.
D.	Self-evident.
E.	Self-evident.

Added Comment

For ordinary strokes, a threshold value of 5 kA could be satisfactory. This may be inconsistent with Priority B(i).

State what potential values you see from observing these (the physical variables of Viewgraph 2) from space. (3)

Problem	Comment
A.	(a) Consolidated and consistent data available through a simplified system. (b) Removal of bias.
B.	It is doubtful if these data can be obtained without complementary ground-based systems. (See Viewgraph 8 also.)
C.	See A above.
D.	Self-evident.
E.	Simplification and coordination.

State whether prefeasibility experiments or analyses are required and define what these are. (4)

Note: The meaning of "prefeasibility" was clarified by Dr. Vaughan. Within his context, it is believed that only the sensor committees need address this question.

Suggest the techniques for measurement from space and contrast with other methods. (5)

Not applicable to the scope of our committee.

Itemize for each observable the measurement parameters; for example: location and time of occurrence, space and time resolution, band width, frequency of observation (minimum sampling time), spacial coverage. (6)

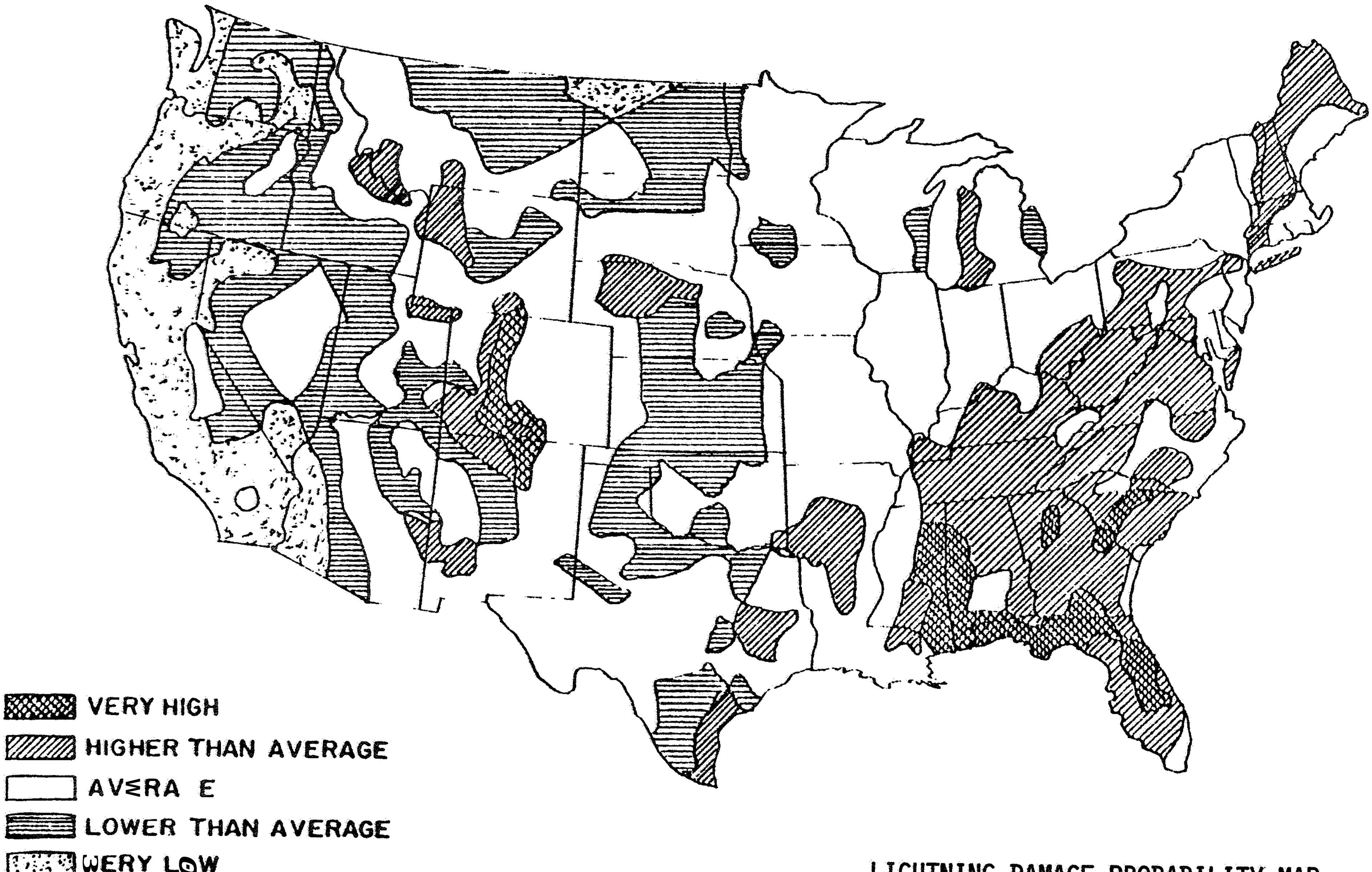
See Viewgraph 2.

Give the data requirements, output format and characteristics required. (7)

Not applicable to our report.

State whether ground truth or other satellite sensor support is required and list the requirements. (8)

Ground-based support is thought desirable for Problems A and C, and required for Problem B.



LIGHTNING DAMAGE PROBABILITY MAP

Map supplied by Edward Cohen, Rural Electrification Administration.
(Based on best available information — draft copy)

ATMOSPHERIC ELECTRICITY AND METEOROLOGY COMMITTEE

H. Frank Eden
National Science Foundation

The Atmospheric Electricity and Meteorology Committee consisted of James Dodge, NASA Headquarters; Bobby Turman, U.S. Air Force; Larry Christensen, UT Space Institute and FWG Associates; William Johnson, NASA Marshall Space Flight Center; Charles Moore, New Mexico Institute of Mining and Technology; Patrick Squires, National Center for Atmospheric Research; Bernard Vonnegut, State University of New York; Lee Parker, Lee Parker, Inc.; and Ralph Markson, Massachusetts Institute of Technology. The viewgraphs used by the chairman in the presentation are given at the end of the report.

The committee discussed the value of lightning data from space from the point of view of research and possible prediction. The techniques committees supplied the majority of the information concerning the feasibility of sensor systems needed to satisfy the atmospheric electricity and meteorology community requirements. The Atmospheric Electricity and Meteorology Committee assumed, as boundary conditions for their discussion, a hierarchy of capabilities for satellite observations of lightning. The research topics discussed fell into the four categories of research on the thunderstorm scale, on middle latitude and tropical cyclones, on the global scale, and on the topic of chemistry and lightning.

The middle latitude and tropical cyclone scales are interesting, although not much is known about lightning associated with frontal systems, large scale cyclonic storms or tropical cyclones. The scale of motion indicates that one needs observations from space to study the phenomena adequately.

Similarly, the chemical effects of lightning are interesting. Recently, the classical problem of how much nitrogen in the earth's atmosphere is fixed by lightning has reemerged as an important input to atmospheric chemistry. Thus, a significant question is what is the contribution of lightning to the global nitrogen budget and also what is the correlation between lightning and the production of other trace species? It is likely that an adequate study of the nitrogen budget needs, as input, measures of the amount of global lightning.

Further discussion of these two subjects was not pursued. Capabilities for measurement of lightning on the thunderstorm scale and global scale will be able to provide information for research on mid-latitude and tropical cyclones and on the topic of chemistry and lightning. The committee considered the thunderstorm scale and global scale in more detail.

On the thunderstorm scale, there are two classes of problems; the first one involves questions of how the clouds become electrified, what are the conditions for lightning production, and how much lightning is produced? The second class of questions is a perennial one of the coupling between lightning production and electrification with other meteorological aspects of the storm system such as the dynamics and the precipitation processes. For example, there is some indication from previous research that the amount of lightning produced correlates well with the height of a thunderstorm and therefore presumably the severity of the storm. Other research has indicated that the radiated noise spectrum may indicate the severity of storms, including the production of tornadoes. Better correlations between atmospheric electricity and storm systems may lead to improved prediction or at least help present prediction systems. Correlations between lightning and precipitation processes and between lightning, convection, and storm severity are also needed. Observations from space may well answer some of these important questions.

The committee emphasized that research on thunderstorms requires that the complete storm system must be observed. This makes space data invaluable. There are indications from astronauts and from U-2 airplane observations of lightning that the storm systems viewed from above appear quite different from the picture presented from observations from ground-based systems alone. A satellite data system would not make it possible to dispense with present ground systems, but would serve as a valuable adjunct. Questions of the electrification of oceanic storms or of small clouds or warm clouds make data from space a requisite.

On the global scale, research areas that would benefit greatly from staellite data are even more obvious. The topics include the reality of the diurnal cycle of global thunderstorm activity, secondly, thunderstorm activity over the land contrasted with over the ocean, climatic changes by the season or by years in the number of storms over the globe, the esoteric but intriguing question of possible solar connections to the earth's weather. If rapid data collection on global thunderstorm activity were available, questions as to whether phenomena such as solar flares affect the production and flow of global electricity might be answered.

The committee outlined certain requirements for data collection on the thunderstorm and global scale. The following requirements are some of the suggestions which were felt to be necessary on a thunderstorm scale. sensitivity, (optical) 10^7 to 10^{12} watts, timing resolution, 30 microseconds, and the ability to distinguish strokes from flashes. A spatial resolution of $\pm$ 4 km and a total grid size of 200 km x 200 km would be required. Real-time information would probably not be necessary unless there were real indications that warning systems could be developed on the basis of the information. Very accurate time fixing would be necessary. Cloud-to-cloud or cloud-to-ground discrimination would be desirable. Information on the current and, in particular, long, continuing currents would be beneficial. Spectroscopic data was discussed, but no definite recommendations were made.

The research requirements indicate the use of geosynchronous satellites, although orbiting data could help build a climatology of thunderstorm activity.

On the global scale, the community has a significant amount of experiences with satellite data. Requirements can be relaxed from those needed on the thunderstorm scale. Counting flashes rather than strokes would suffice to determine the global amount of lightning. The spatial resolution could be relaxed to perhaps ± 10 kms. Otherwise, the requirements for global scale data are quite similar to those of the thunderstorm scale.

The Optical Techniques Committee indicated that it would probably be possible to measure flash rates and perhaps strokes and intensity. Cloud-to-ground discrimination was possible. The resolution requirements seemed less difficult than the time requirements. To solve some of the problems of solar-weather relations, it would be necessary to build up a hemispheric picture in perhaps five minutes. This is a severe time requirement. The Optical Techniques Committee indicated that the requirements for information on currents are feasible.

The Electromagnetic Techniques Committee indicated that hybrid systems will probably be most beneficial. RF measurements would supplement optical techniques when visible signals are attenuated by cloud cover as, for example, with deep clouds. The RF Committee indicated that information in the frequency range of 40-50 MHz is possible. This would be valuable for questions of the spectrum of RF emissions relating to increasing storm severity and possible tornado production.

Not enough is known about the spectrum at higher frequencies or of information that might be obtained about lightning in the 1 GHz range. An examination should be made of what information can be received in space in the 50 MHz range.

There were several opportunities for ground truth projects. There are a number of possible ground truth experiments which have already been performed or will be performed for lightning location and total activity information (e.g., Krider Forest Service Network). In the TRIP 1979 Project this summer in New Mexico, a U-2 airplane will be flying while the DMSP satellite will pass with its lightning sensor. There are also a number of other opportunities in the United States for obtaining ground truth information. There are a variety of experiments aimed at investigating severe storms over the next several years, and it appears that it would not be particularly difficult to obtain fixed ground truth for atmospheric electricity and lightning production. Of course, the question of how to obtain these ground truths in the tropics or over the oceans must be addressed.

RECOMMENDATIONS

- The Committee recommended a graduated program of research to improve our capabilities in lightning measurements from satellites. This would involve aircraft measurements over thunderstorms, probably utilizing U-2 aircraft; measurements from the Space Shuttle; and increasing planned use of lightning detectors on satellites. In addition, flights of opportunity should be sought.

- Mesoscale meteorological experiments, such as SESAME or the activities of the Convective Storms Division of NCAR, should include ground-based measurements of lightning to relate the activity to the radar, aircraft and satellite data. The managers of such experiments should be aware of the possibilities of the dates and timing of current satellite lightning measurements over their location coinciding with their field days.

- Further research is needed on the information content of the entire spectrum of emissions for optical through high radio frequencies from thunderstorms when viewed from above.

VIEWGRAPHS USED DURING THE PRESENTATION

USER COMMITTEE: (1)

ATMOSPHERIC ELECTRICITY & METEOROLOGY

CONSIDERED:

1. THUNDERSTORM SCALE
2. MID LAT & TROPICAL CYCLONE
3. GLOBAL SCALE
4. CHEMISTRY & LIGHTNING

SCIENTIFIC QUESTIONS: (2)

THUNDERSTORM SCALE

LOCATION OF ↯ IN ACTIVE CLOUDS

RELATION OF ↯ TO PRECIPITATION

RELATION OF ↯ TO CONVECTION (TURRETS)

LIGHTNING BUDGET

OCEAN-LAND CONTRAST

THUNDERSTORM SCALE (CONTINUED) (3)

RELATION OF ↯ AND SEVERE STORMS

CONDITIONS FOR ↯ (WARM CLOUDS, ETC.)

GLOBAL SCALE (4)

1. DIURNAL CYCLE?
2. LAND-SEA CONTRAST
3. CLIMATOLOGY OF STORMS
4. POSSIBLE SOLAR CONNECTIONS

THUNDERSTORM SCALE REQUIREMENTS (5)

SENSITIVITY	10^{7}-10^{12} WATTS
TIMING RESOLUTION	30 μSEC
FLASH/STROKE	— STROKE
SPATIAL RESOLUTION	4 KMS
GEOGRAPHY	200 x 200 KMS
REAL TIME	NO (WARNING?)
C-G OR C-C DISCRIMINATION	YES
CONTINUING CURRENTS	YES
GEOSYNC OR ORBITING	GEOSYNC
SPECTROSCOPIC DATA	?

GLOBAL SCALE REQUIREMENTS (6)

1. RELAX SPATIAL RESOLUTION
2. COUNT FLASHES
3. GENERALLY SIMILAR TO CLOUD SCALE
4. EXPERIENCE GUIDES

OPTICAL (7)

1. FLASH RATE/DENSITY
2. INTENSITY
3. C-G OR C-C?
4. RESOLUTION
5. CONT. CURRENT?

RF (8)

(JAPANESE EXPERIENCE 2-25 MHZ)

1. SUPPLEMENT OPTICAL WHEN THEY ARE ATTENUATED
2. BURST RATES ~ 50 MHZ (BILL TAYLOR)
3. VLF DATA LOST? (ATTENUATED)

RESEARCH: QUESTIONS ON TECHNIQUES (9)

1. WHAT INFORMATION ON ⚡ AT 1 GHZ
2. EXAMINE EXPERIENCE ON ~ 50 MHZ DATA IN SPACE
3. SPECTRAL INFORMATION ON ⚡

GROUND TRUTH (10)

1. "KRIDER" NETWORK
2. TRIP 79 (U-2 + PBE)
3. OTHER OPPORTUNITIES IN UNITED STATES
4. TROPICAL/OCEAN?

WORKSHOP ON "THE NEED FOR LIGHTNING OBSERVATIONS FROM SPACE"

Comments by

John M. Butler, Jr. *

NASA Marshall Space Flight Center

The workshop planning and coordination was excellent. Over the period of two and one half days, I sat in on at least one session of each committee, and I found the committee participants to be objective, interested in the subject, and generally of common opinions.

The committee findings were overwhelmingly positive about the question of whether or not observation of lightning from space is desirable. The committees also provided useful data on the types of measurements desired from space. Interest was expressed in both low and high (geosynchronous) orbits, although the most useful of the two types is the geosynchronous.

Although a good bit of data has been collected on lightning, the degree of "unknowns" regarding this phenomena, its cause-and-effect relationships, and some of the observational techniques were surprising. For example, there seemed to be major questions about the degree of background noise which would be encountered in observations from space.

There was an interest shown by the attendees in the Air Force Piggy Back Experiment (PBE) even though this was a very small (1.5 lbs) and limited experiment. NASA could probably benefit from such interest, and it might be possible to find some early LEO or GEO satellite which could make available a small amount of space for a piggy-back experiment(s) of improved capability. Preliminary experiments of this type might also be beneficial in defining the concepts and instrumentation needed for more detailed experiments to follow. Another area which should be investigated for early application is the potential for pointing any satellite (even solar or celestial astronomy satellites, for example) towards the earth occasionally to gather data on lightning flashes, using only its existing complement of instruments. Investigation of a more comprehensive and capable dedicated lightning detection system should be carried out also, for possible later application as a satellite or element of a space platform.

Lightning detection from space also might offer an opportunity for application of a "Tether" system, if the tether sensor package could be extended down as far as the upper regions of the ionosphere. One of the areas of user interest is the "global model" associated with thunderstorm activity, including the electric field effects within the ionosphere.

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* Workshop Advisor on Space Platforms

WORKSHOP ON "THE NEED FOR LIGHTNING OBSERVATIONS FROM SPACE"

Comments by

Frank H. Emens*

NASA Marshall Space Flight Center

The NASA/UTSI sponsored workshop on observation of lightning phenomena from space was very well planned and coordinated. During the workshop, the potential impacts on data handling were assessed by monitoring the activities of the two sensor committees with the following results.

It was not the goal of the workshop to design the electromagnetic sensing instrumentation required. It was difficult, therefore, to judge what data handling problems might be encountered. The impression was received, however, that while the raw analog data generated by the electromagnetic sensor may require a prohibitively high transmission bandwidth, techniques were available to extract and encode only the parameters of interest for transmission. It seemed apparent that a carefully designed series of experiments is necessary to determine which parameters are of interest and to define the on-board processing required to do the parameter extraction.

The Optical Sensors Committee defined possible sensor configurations to address the requirements matrix generated by the user committees. Rigid interpretation of this requirements matrix would result in a sensor generating hundreds of megabits per second of raw data. It was recognized that such rates would be excessive and that development effort would be required to develop on-board processing techniques to perform data compression.

The on-board processing techniques are highly dependent upon the sensor design, the sensor management strategies used, and the parameters actually required on the ground. It is essential that development of the processing algorithm, if not the actual processing hardware, be concurrent with and interactive with the sensor development.

The raw data rate from the sensor, which directly affects the processor speed requirement, is highly sensitive to some of the items in the user requirements matrix. It is important, therefore, to plan for a detailed trade study setting sensor and data system costs against user benefits. More experimental work is necessary before an operational sensor system can be adequately delineated.

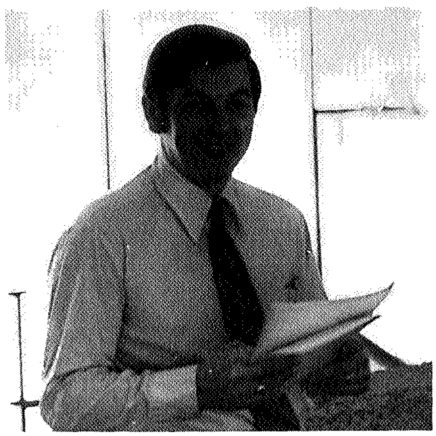
The results of the workshop have been discussed with Marshall Space Flight Center personnel involved with the NEEDS (NASA End-to-End Data

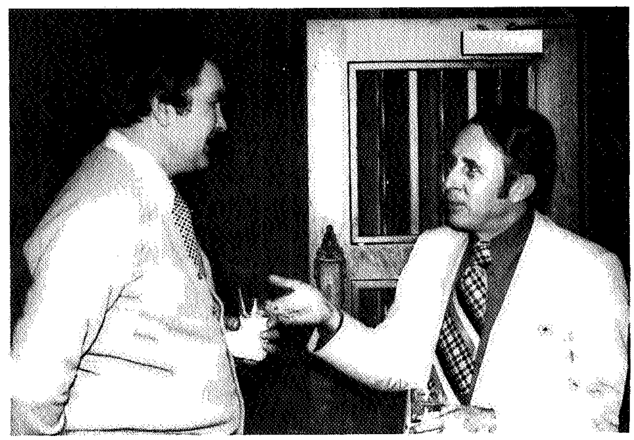
* Workshop Advisor on Data Management

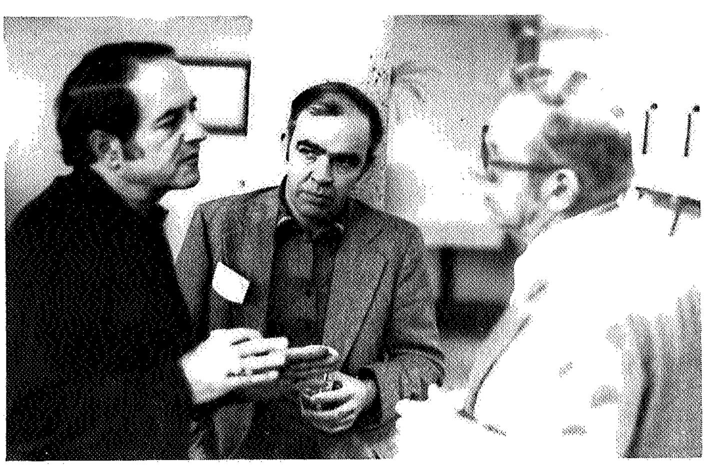
System) program with the conclusion that, given adequate performance from the on-board data processing, the sensors discussed at the workshop could be handled within the **NEEDS** framework. The **NEEDS** program proposes to supply real-time transfer of data at burst up to 50 megabits to a user. In the case of a lightning survey satellite, this user would be required to disseminate the information to all those user sites requiring short term warnings. At a substantially slower average rate (not specified at this time) data can be transferred into archival storage and into a data base where it can be accessed by those users requiring long-term statistical data rather than short-term warnings.

SECTION VII

CONCLUDING REMARKS







CONCLUDING REMARKS

James C. Dodge
NASA Headquarters

A lot has been said in the last two and one-half days, and it is very difficult to sum it up in one or two minutes. First, it has been demonstrated here that there is no doubt at all that there is a keen interest on the part of a wide variety of potential users concerning lightning observations from space. Secondly, I think the engineering and operational users present had intimate and specific knowledge of their engineering requirements. This alone points to lightning observations from space as a goal that is well worth pursuing. There is also no doubt that on the other end of the spectrum the optical and RF technologists knew very well what could be measured and if indeed it was present in the lightning signal at a particular altitude at which a potential satellite might fly. Between the two sensor committees there appeared to be a shortage of information concerning the specific optical and RF emissions that one could expect at a particular time. In fact, there appeared to be a shortage of information of just what lightning characteristics might tell us concerning specific user requirements such as intensity, power, waveform shape, relationship to storm severity, and any one of a variety of potential requirements. Lightning research from space appears very encouraging and looks like a very profitable and potential line of research; and there may be, in fact, a satellite at the end of the road. The satellite was not designed here in these last two and one-half days; however, one could not really expect that to be accomplished in such a short period of time.

Everyone was very cooperative, very knowledgeable and the workshop has provided a research and development program which will lead from what is now known to a determination of whether or not lightning characteristics can be quantified from space. Obvious needs exist on the part of many of the users, albeit quite a matrix of needs, but still the needs can probably be classified into those which can and cannot be done once more is known about what comes out of the tops of thunderstorms. The beginnings, at least, of a R&D program have been well defined, and it is remarkable what has been accomplished in the last two and one-half days.

Thanks go to all those participating in the workshop for taking the time to join us and, on behalf of NASA Headquarters and NASA Marshall Space Flight Center, our sincerest thanks is extended to all those who attended. Specifically thanks go to the chairmen: Frank Eden, Edwin Whitehead, Rodney Bent, Richard Orville, and Lothar Ruhnke. These individuals and their devotion pulled the workshop together and made it what it was. It was one of the most successful workshops I have ever attended. Thanks go also to Walter Frost for being such a gracious host and providing the facilities. It is hoped that last, but not least, this workshop provided an opportunity for all of you to not only meet with old friends, colleagues, and associates, but to meet new people who have similar interests. I hope that each individual here has gained from the workshop. NASA has certainly gained because this workshop has provided a unified approach which can lead to a program of lightning observation from space.

APPENDIX

WORKSHOP ATTENDEES AND PARTICIPANTS

WORKSHOP ON THE NEED FOR LIGHTNING OBSERVATIONS FROM SPACE

Roster of Workshop Attendees and Participants

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APPROVAL

PROCEEDINGS: WORKSHOP ON THE NEED FOR LIGHTNING OBSERVATIONS FROM SPACE

Edited By Larry S. Christensen, Walter Frost, and William W. Vaughan

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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